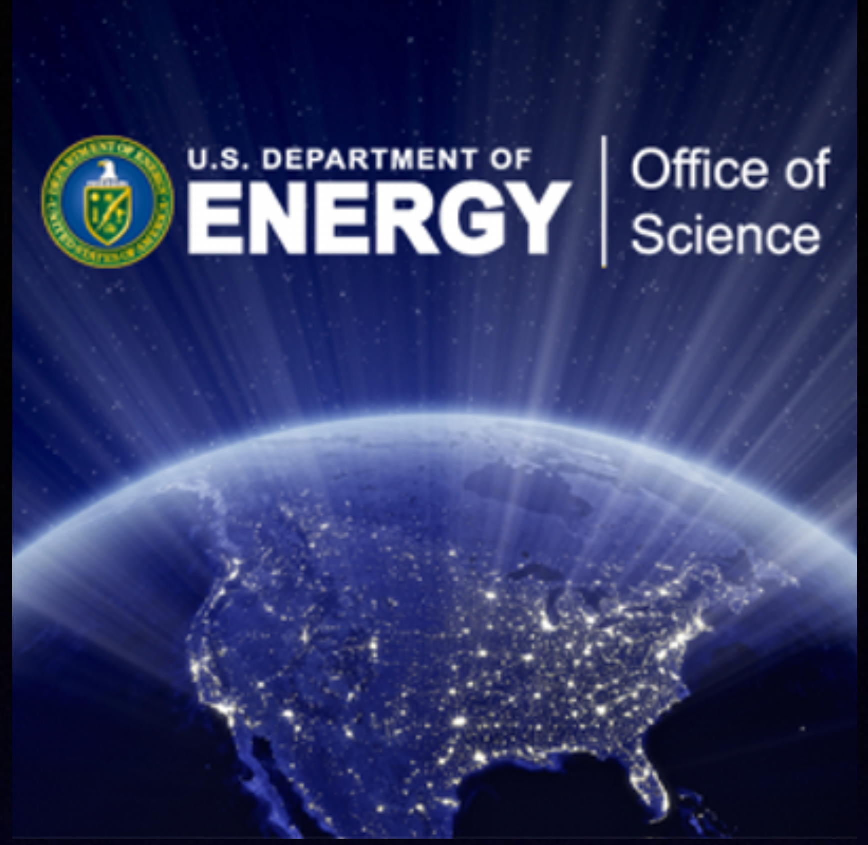


# *Pygmies, Giants, and Skins: Laboratory Experiments Informing the Equation of State*

*(Amherst, October 2022)*

J. Piekarewicz

The 208 **P**b **R**adius **EX**periment **X**

and Neutron Rich Matter
in the Heavens and on Earth

August 17-19 2008

Jefferson Lab
Newport News, Virginia

PREX is a fascinating experiment that uses parity violation to accurately determine the neutron radius in $^{208}$Pb. This has broad applications to astrophysics, nuclear structure, atomic parity non-conservation and tests of the standard model. The conference will begin with introductory lectures and we encourage new comers to attend.

For more information contact horowit@indiana.edu

Topics

- Parity Violation
- Theoretical descriptions of neutron-rich nuclei and bulk matter
- Laboratory measurements of neutron-rich nuclei and bulk matter
- Neutron-rich matter in Compact Stars / Astrophysics

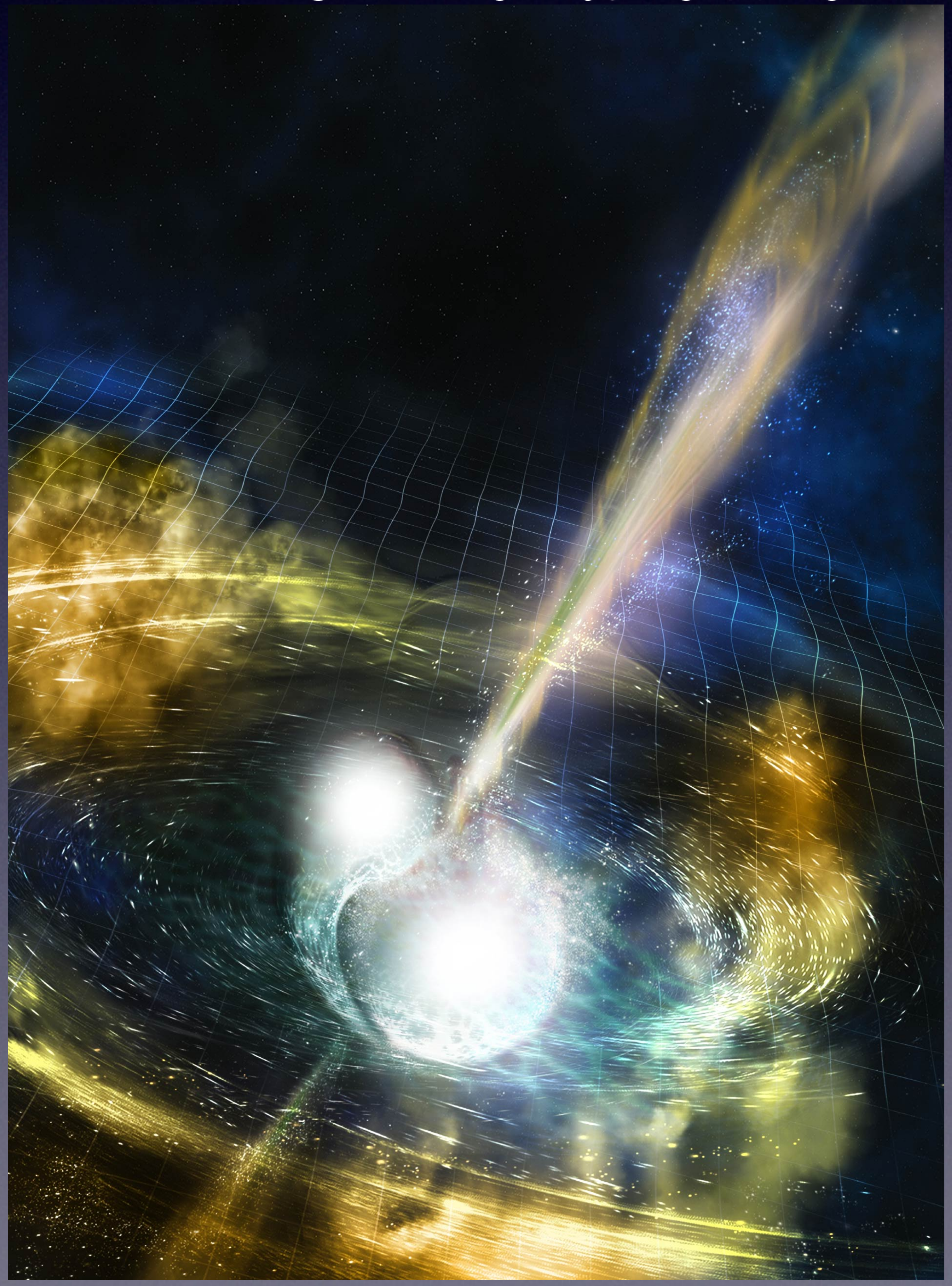
Website: http://conferences.jlab.org/PREX

Organizing Committee

Chuck Horowitz (Indiana)
Kees de Jager (JLAB)
Jim Lattimer (Stony Brook)
Witold Nazarewicz (UTK, ORNL)
Jorge Piekarewicz (FSU

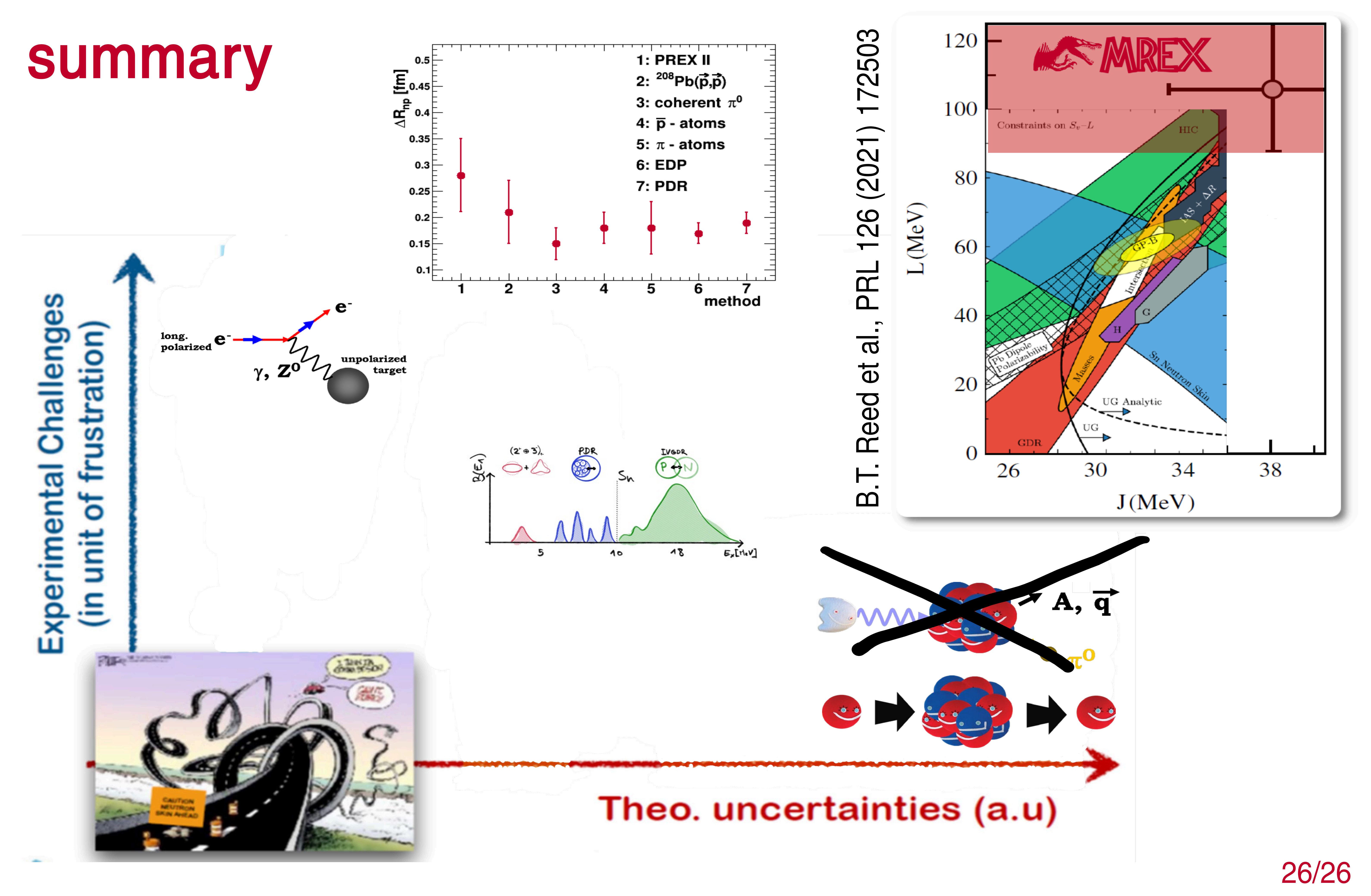
Sponsors: Jefferson Lab, JSA

Giant (Hercules) Awakes and Drives off the Pygmies by Lucas Cranach The Younger (1551)



# nuclear physics experiments

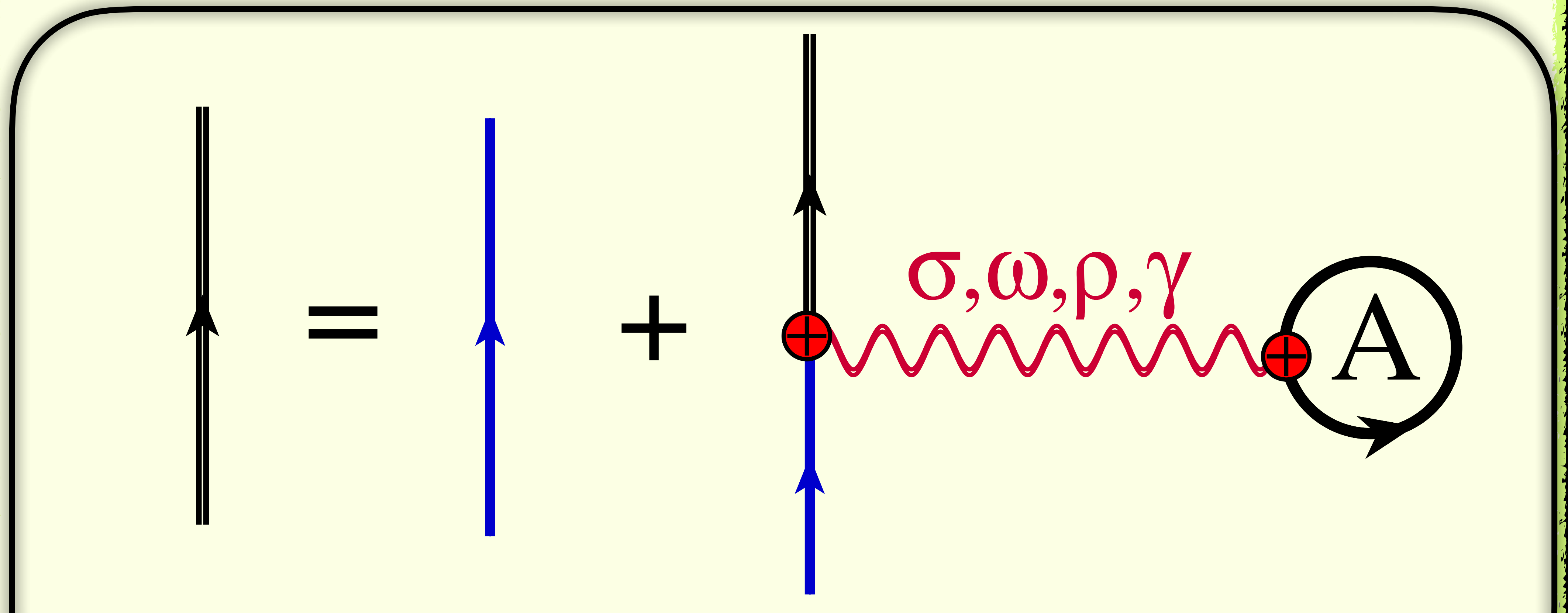
**Michaela Thiel**
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz



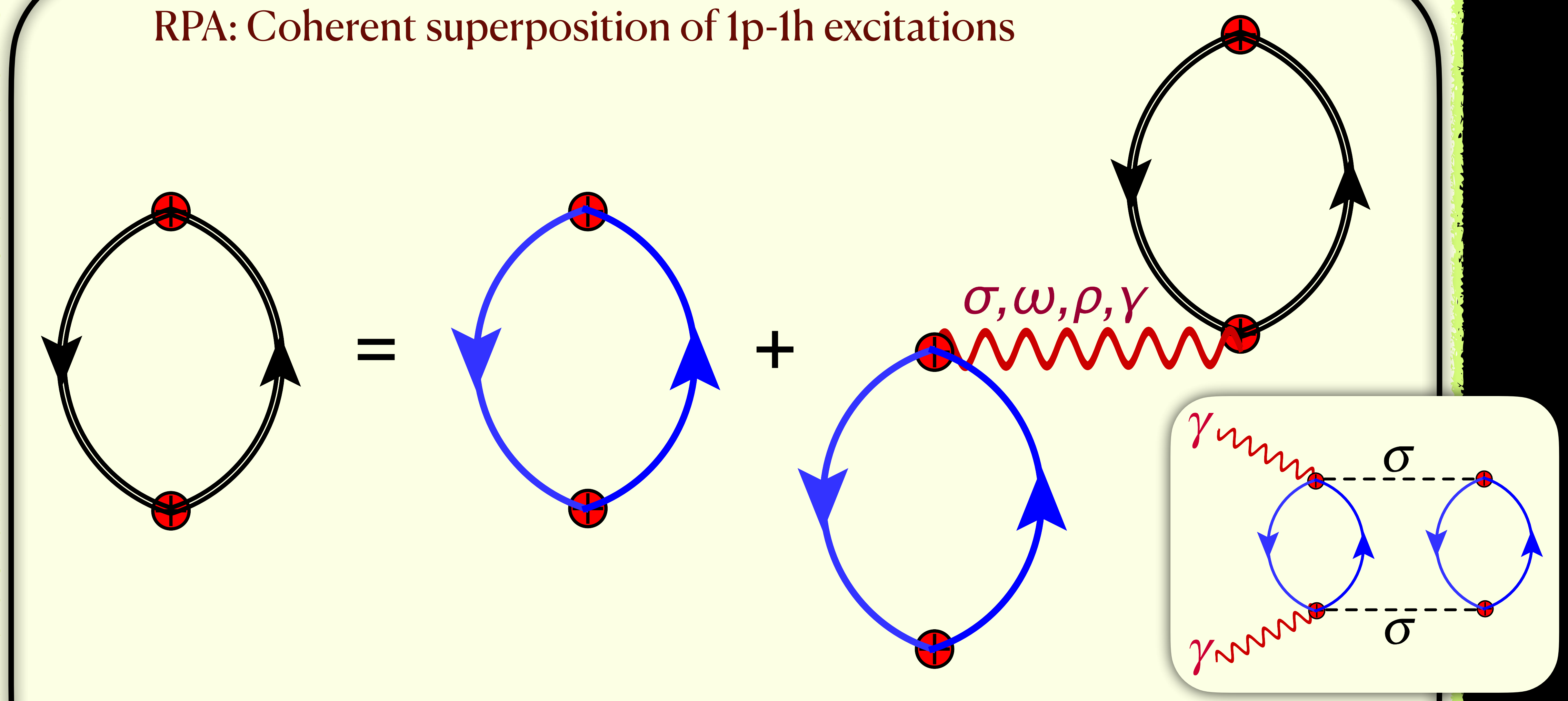
## summary

B.T. Reed et al., PRL 126 (2021) 172503

# Covariant Density Functional Theory



Self-consistent DFT ground state



Linear response of the DFT ground state

Walter Kohn
Nobel Laureate
Chemistry 1998

## Anatomy of a self-consistent Covariant DFT calculation

The Hohenberg-Kohn Theorem: The ground state energy can be obtained variationally: the density that minimizes the total energy is the exact ground state density

- Empirical parameters calibrated to physical observables
- Ground state properties (charge and weak charge densities) emerge from functional minimization
- Collective excitations (e.g., electric dipole response) is the consistent linear response of the ground state to a small perturbation
- Pros: Consistent formalism respects fundamental symmetries
  (gauge invariance and decoupling of spurious states)
- Cons: Misses important physics — such as 2p-2h excitations
  (important contribution to the width off the resonance)

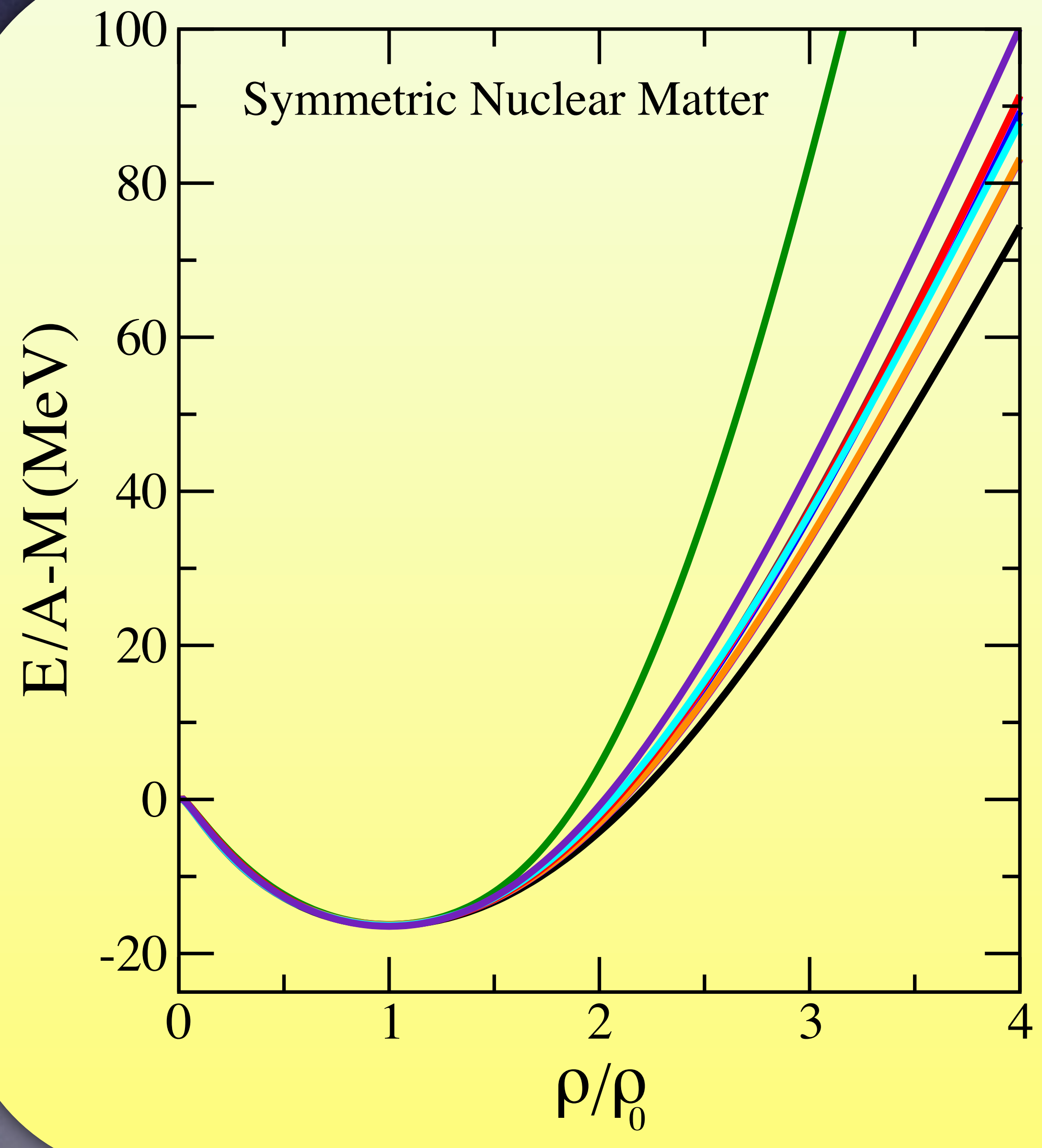
From finite nuclei to neutron stars!

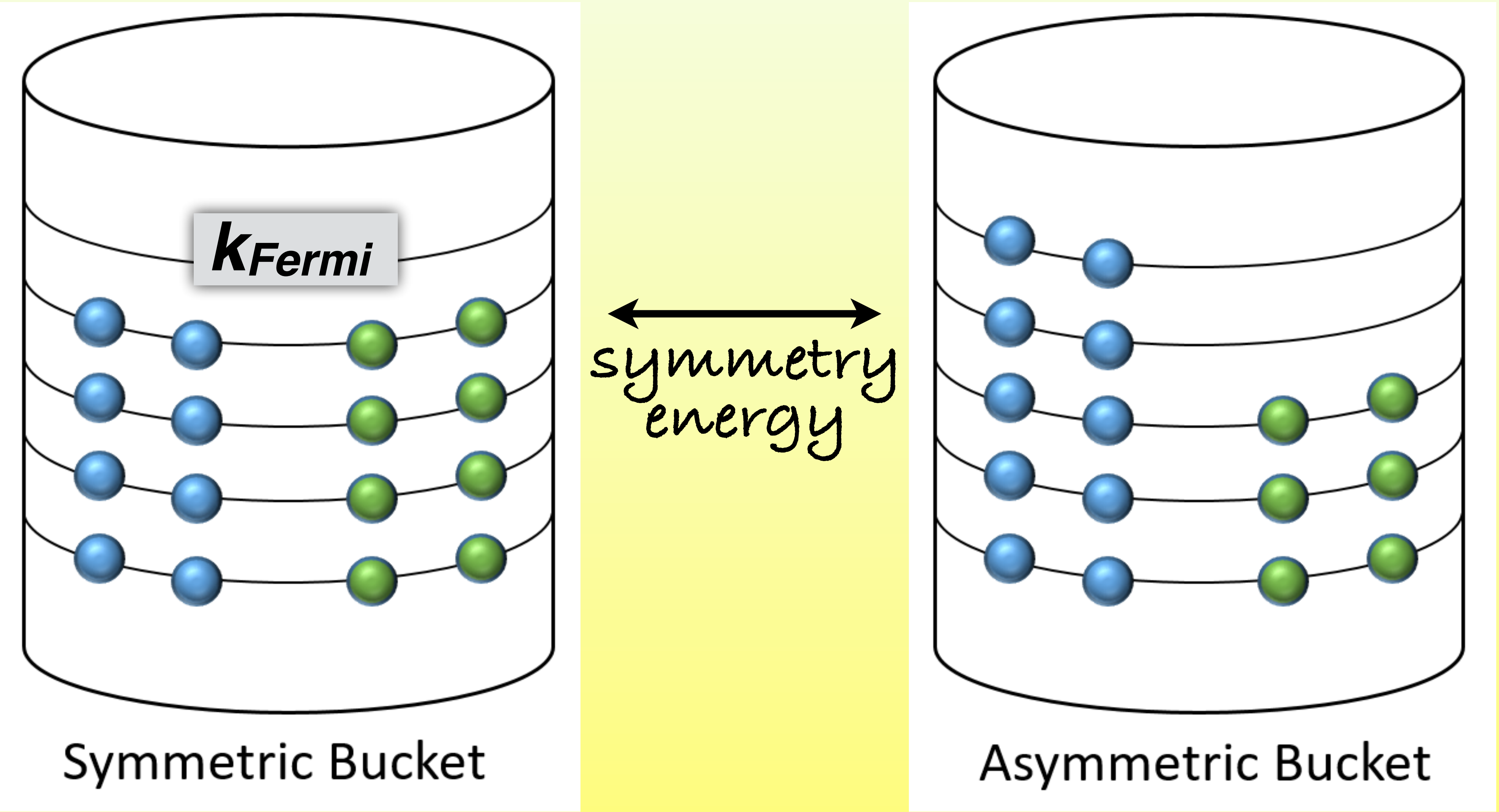
# The Equation of State of Neutron-Rich Matter

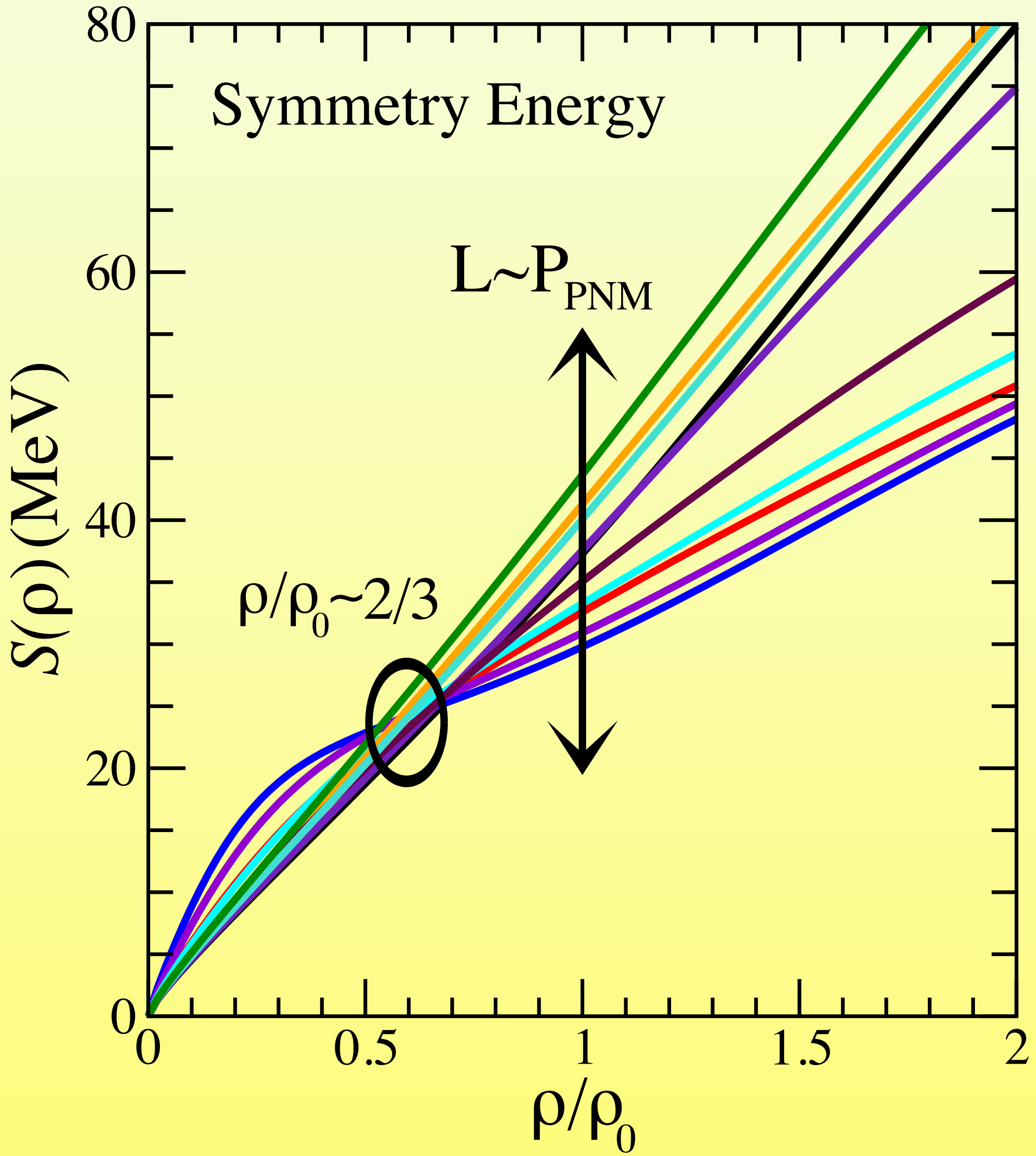
- Two conserved charges: proton and neutron densities (no weak interactions)
- Equivalently; total nucleon density and asymmetry: $\rho$ and $\alpha$=(N-Z)/A
- Expand around nuclear equilibrium density: $x=(\rho-\rho_0)/3\rho_0$; $\rho_0 \simeq 0.15$ fm-3

$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + \boxed{Lx} + \frac{1}{2}K_{\rm sym}x^2\right)\alpha^2$$

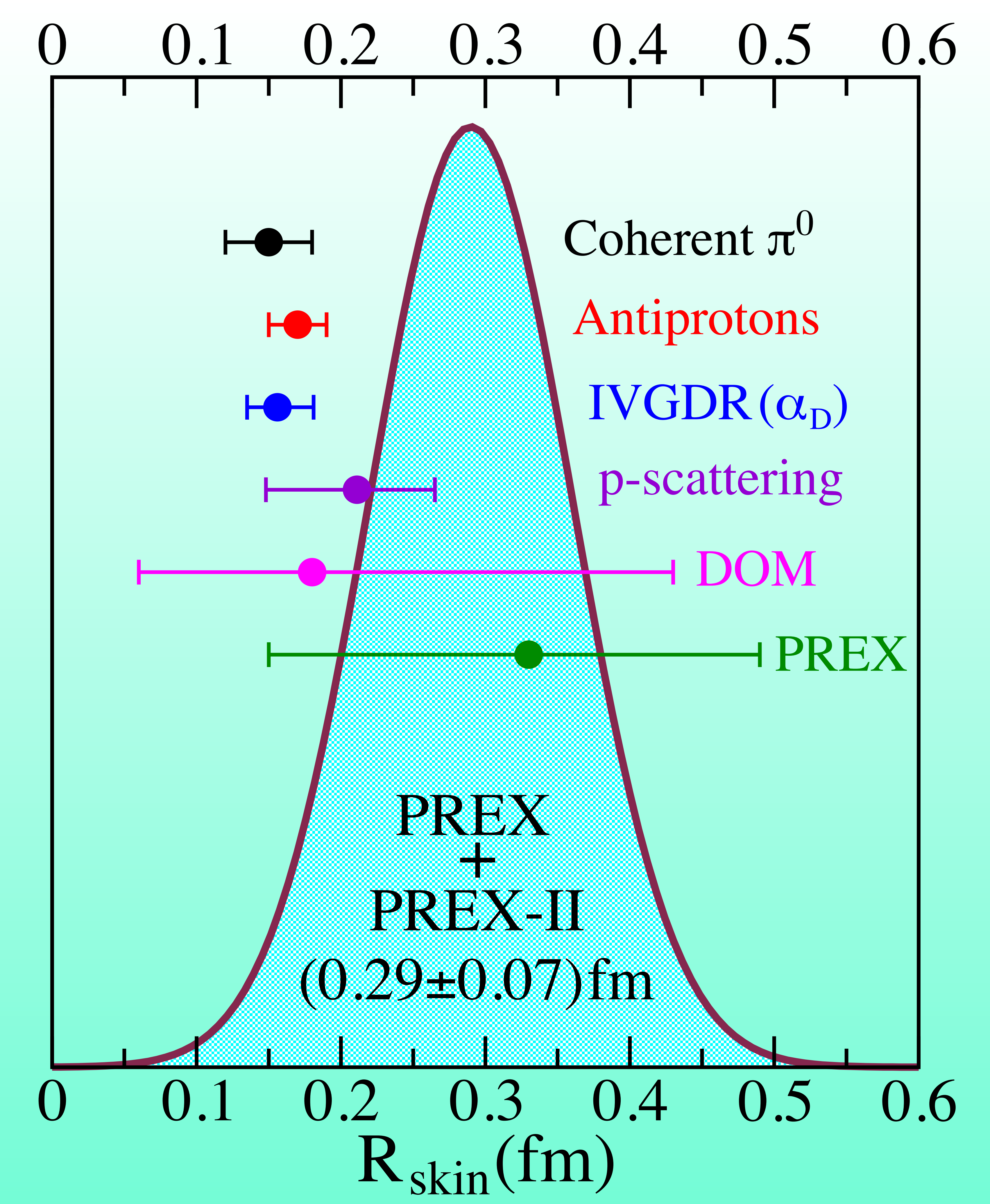
- Density dependence of symmetry energy poorly constrained!!
  "L" symmetry slope ~ pressure of pure neutron matter at saturation







# *Tension between PREX and other experimental determinations of $R_{skin}$*



**MREX**

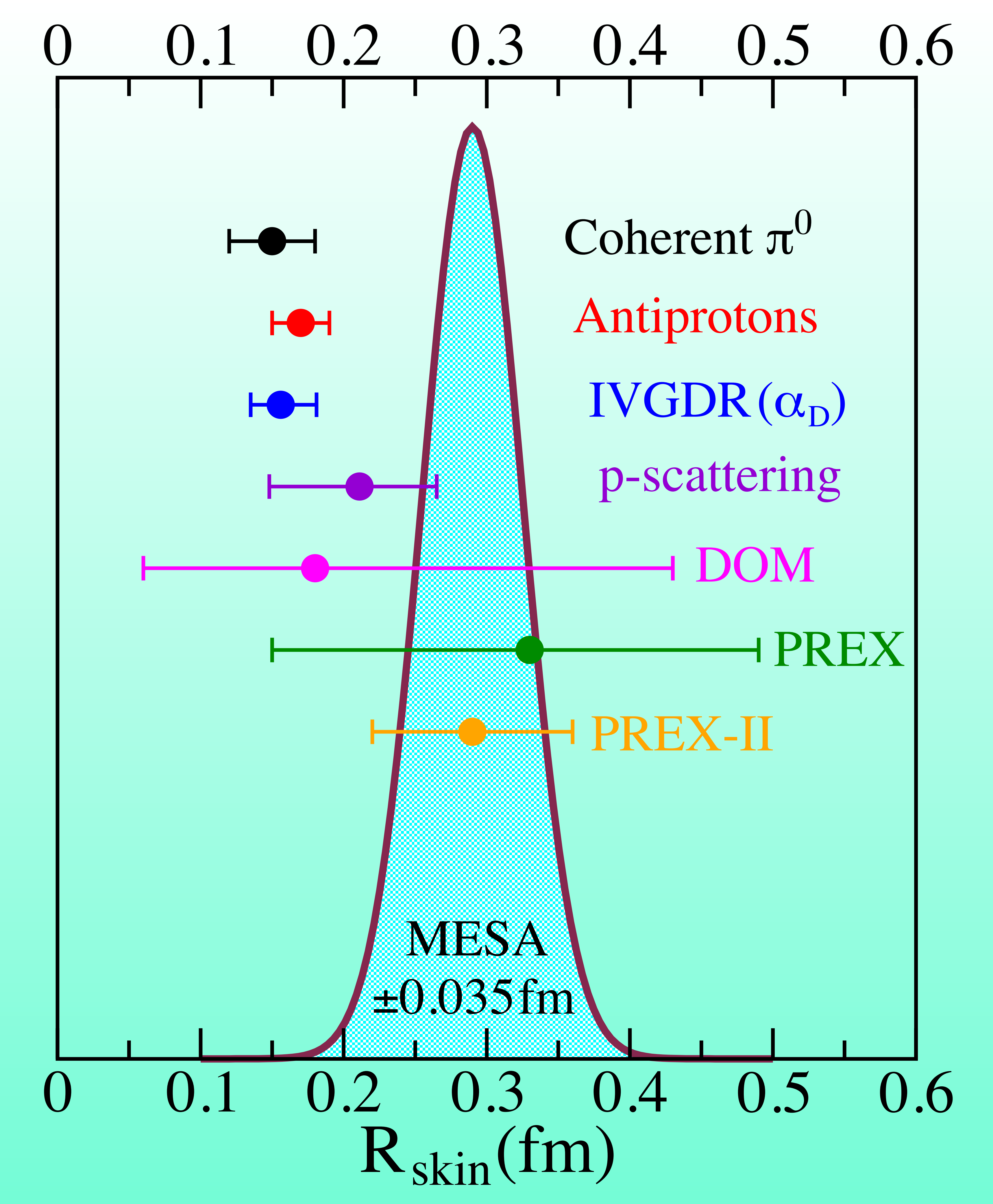
Michaela Thiel

Institut für Kernphysik, Johannes Gutenberg-Universität Main

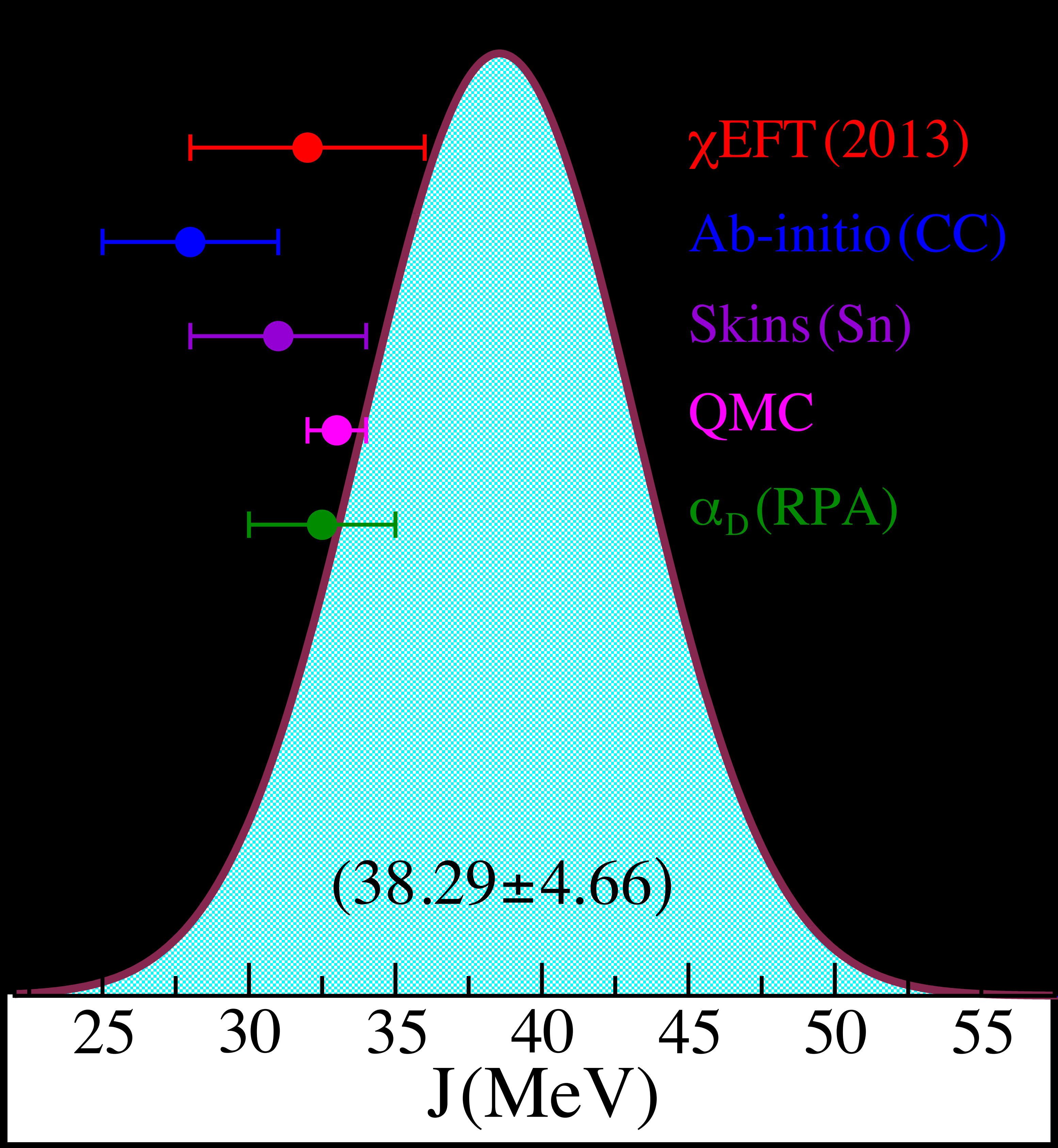
Neutron Skins of Nuclei
MITP workshop
May 17 – 27, 2016
Mainz, Germany

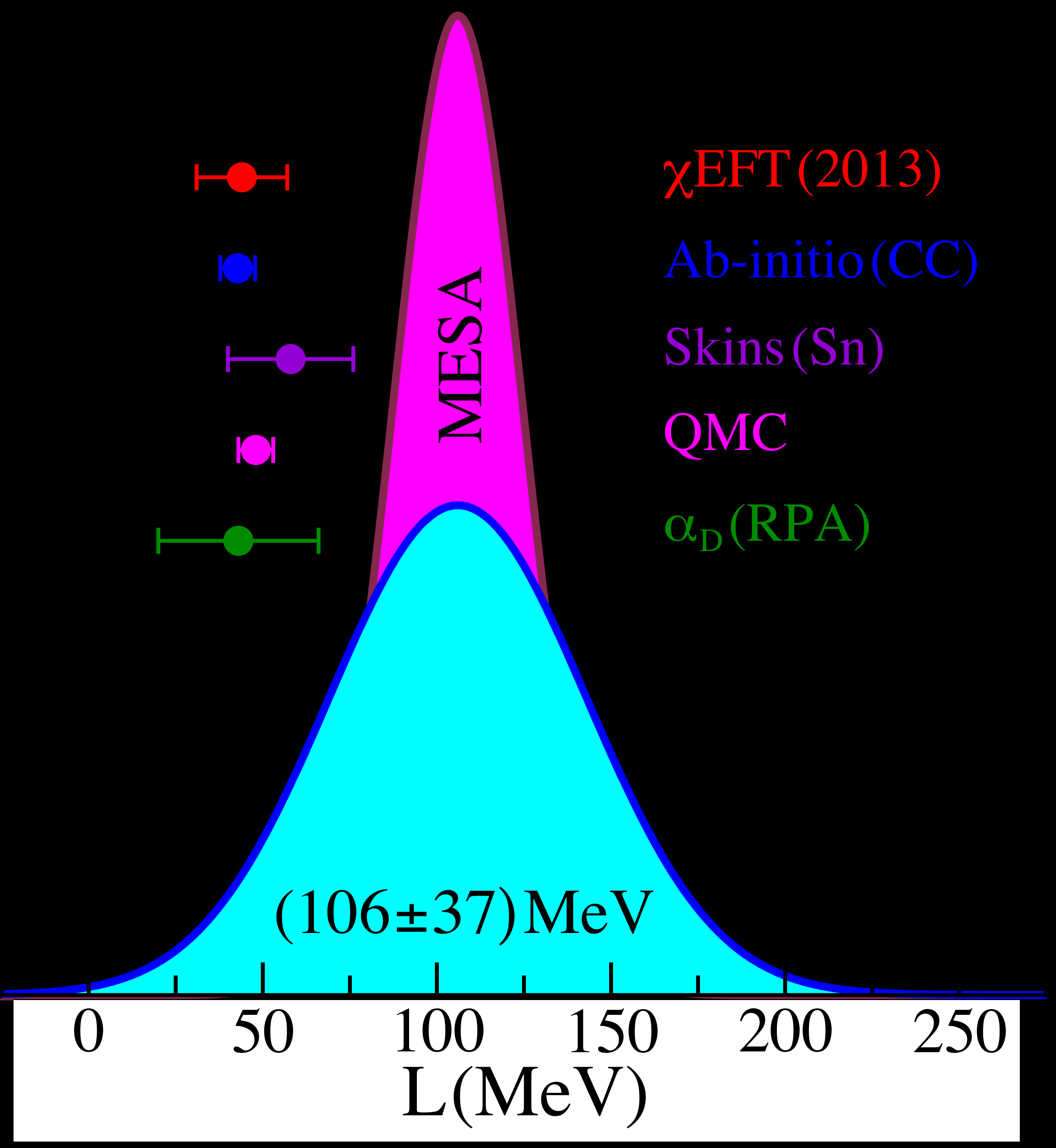
# The Present: PREX
# The Future: MREX
# A Compelling Science Case

- MREX @MESA will provide the stringent constraints on the EOS of neutron-rich matter at saturation density
- An additional measurement can also constrain the entire baryon density of $^{208}$Pb and provide unique insights into the saturation mechanism
- MREX will provide fundamental anchors for future campaigns at FRIB and other future exotic beam facilities



# PREX-2 Constraints on the EOS of Neutron Rich Matter

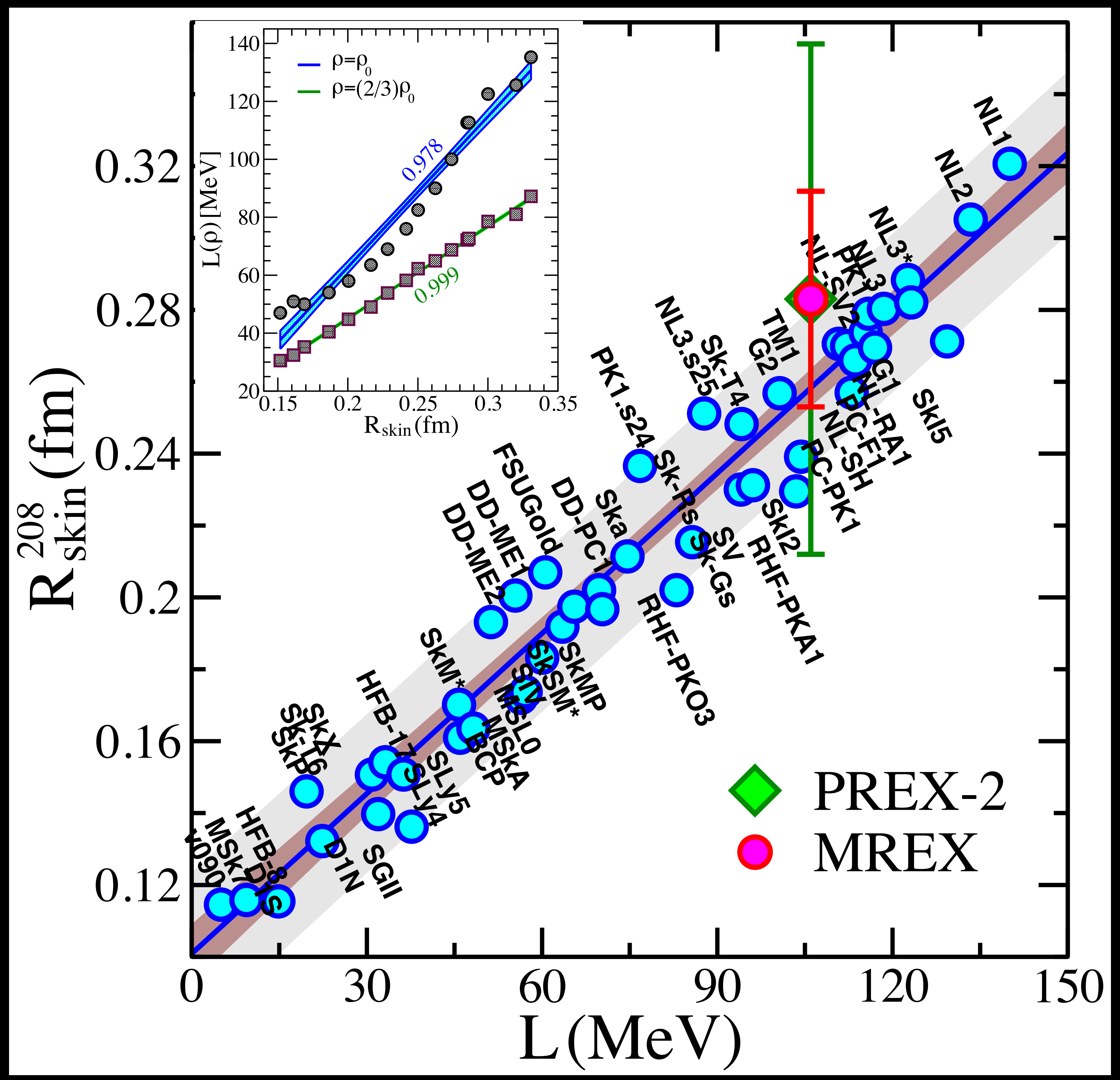




# Validating the Correlation

$$S(\rho_0) \approx \left(E_{\rm PNM} - E_{\rm SNM}\right)(\rho_0) = J$$

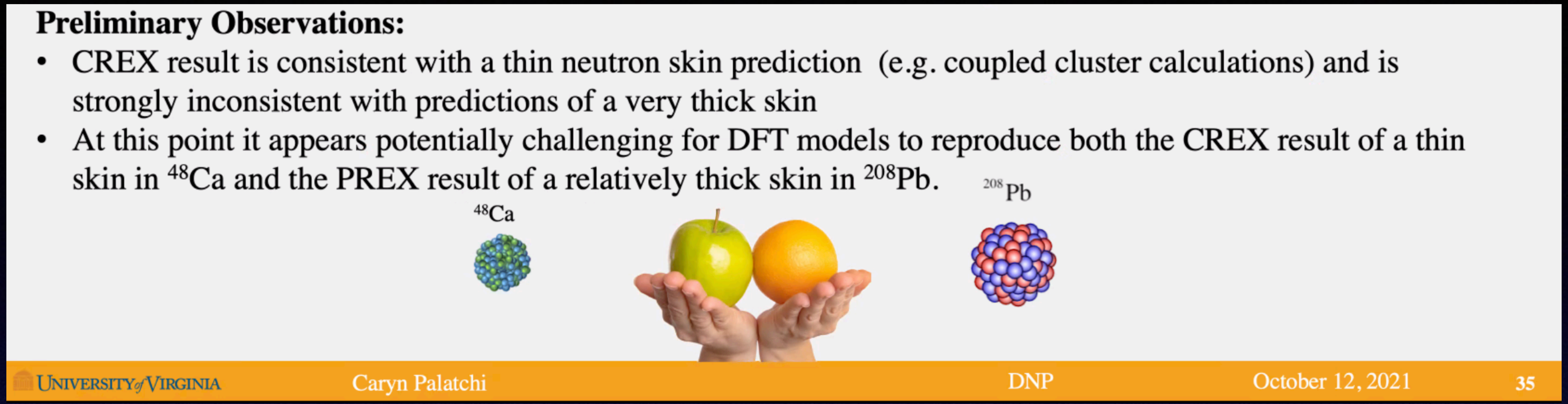
$$P_{\rm PNM} \approx \frac{1}{3} L\rho_0 \ \text{(Pressure of PNM)}$$



*Tension between PREX and predicted bulk properties of the symmetry energy at saturation density— yet "PREX error is still too large"*

# Who Ordered That?

Isidor Isaac Rabi



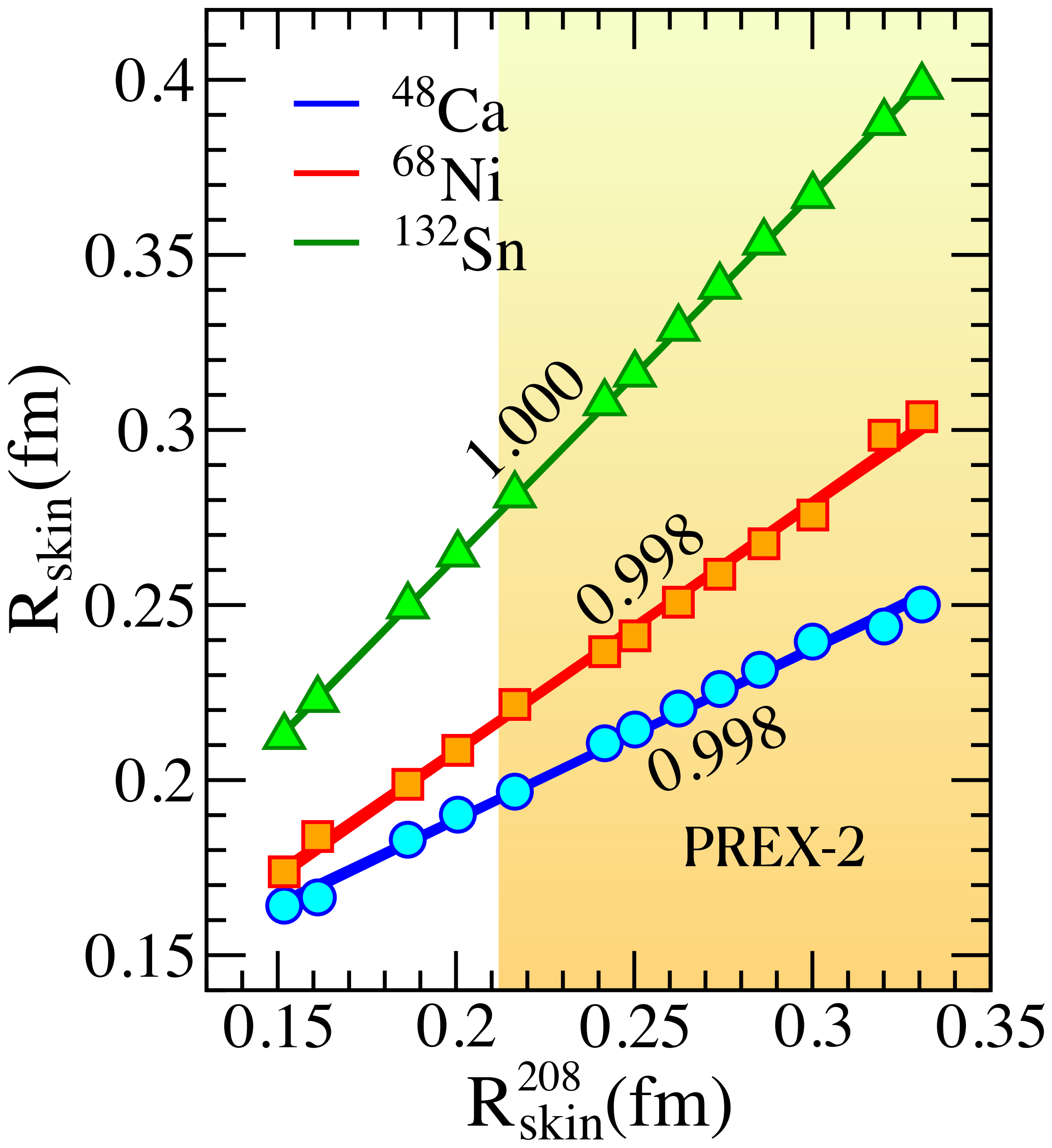
**Preliminary Observations:**

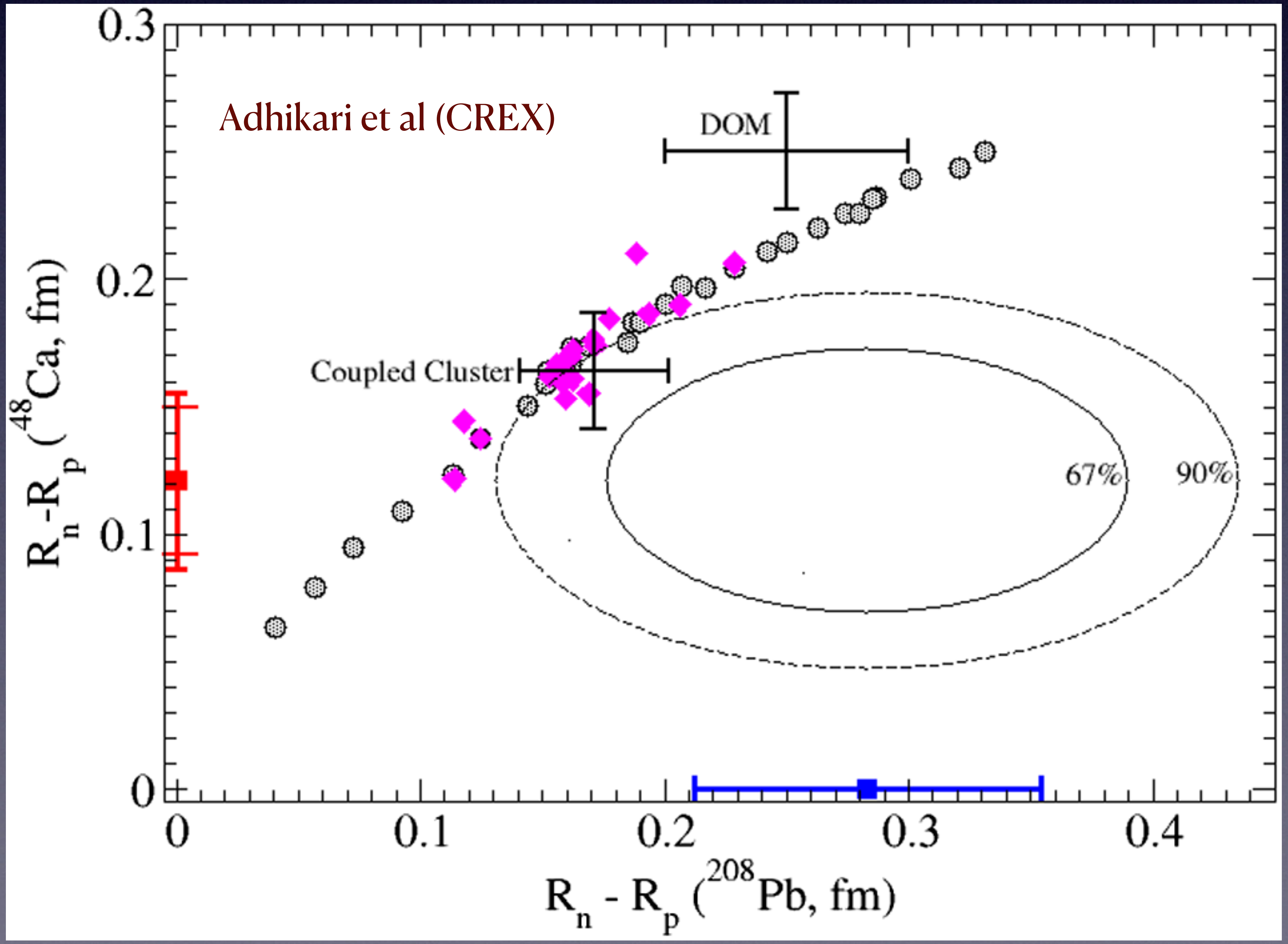
- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin
- At this point it appears potentially challenging for DFT models to reproduce both the CREX result of a thin skin in $^{48}$Ca and the PREX result of a relatively thick skin in $^{208}$Pb.

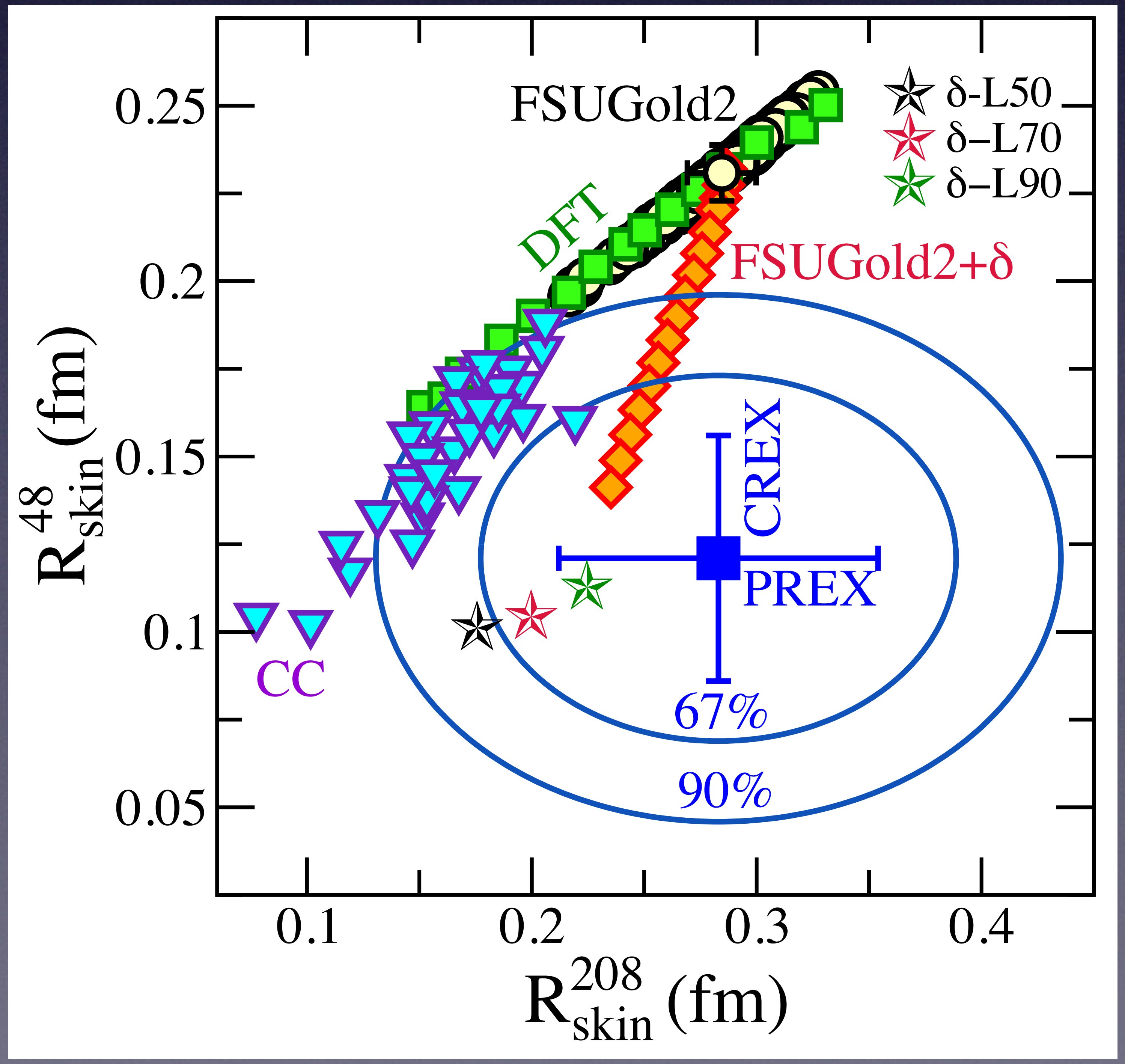
University of Virginia Caryn Palatchi DNP October 12, 2021 35

**No theoretical model that I know of can "comfortably" reproduce both!**

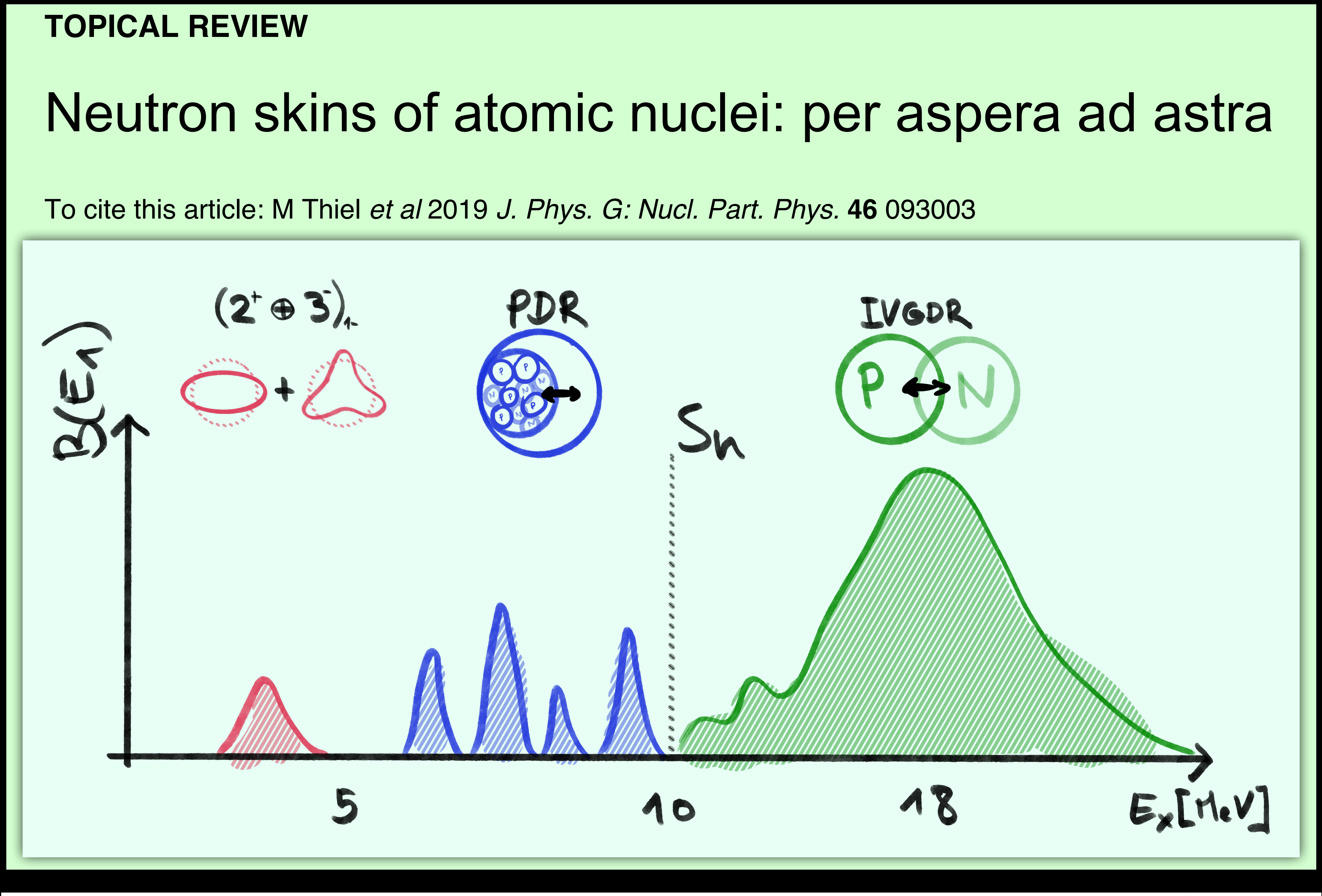
**How does one break the fairly strong correlation between both?**







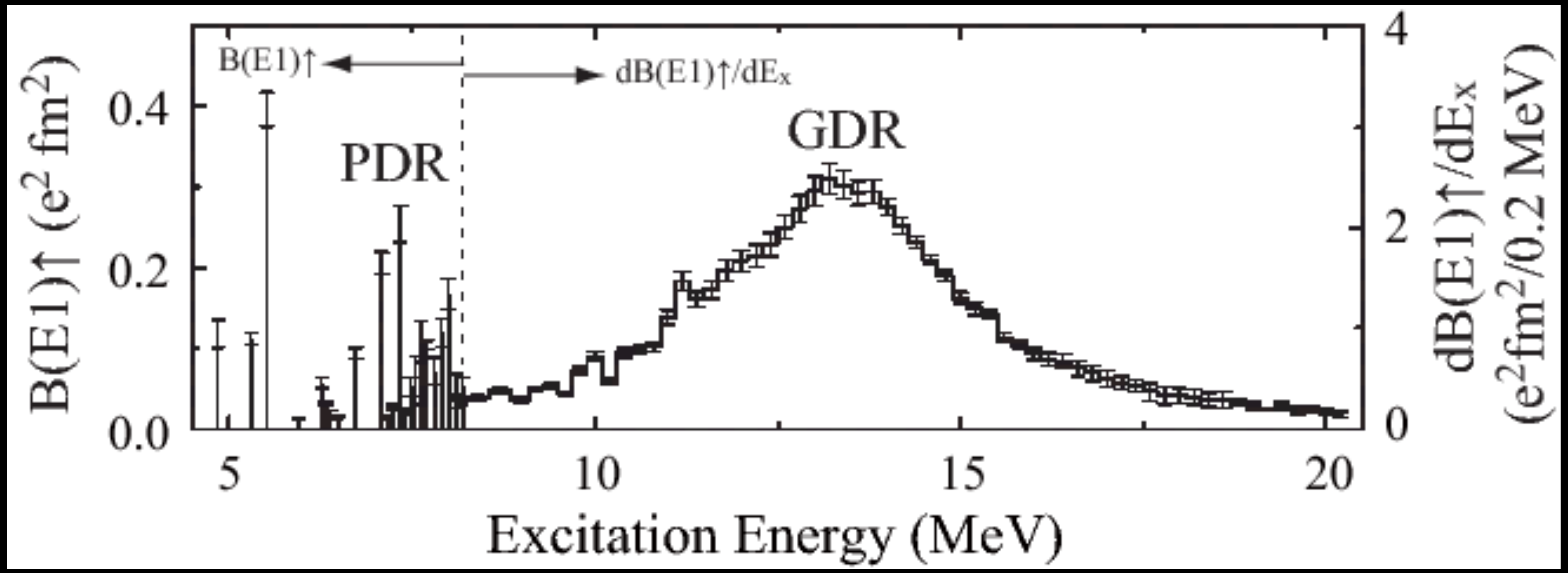
# Electric Dipole Response



TOPICAL REVIEW

Neutron skins of atomic nuclei: per aspera ad astra

To cite this article: M Thiel *et al* 2019 *J. Phys. G: Nucl. Part. Phys.* **46** 093003



## IVGDR: The quintessential nuclear excitation

- Out-of-phase oscillation of neutrons vs protons
  Symmetry energy acts as restoring force
- Pygmy dipole resonance a soft mode with neutron rich skin oscillating against the symmetric core
- High quality data from RCNP, GSI, HIGS, …
  On a variety of nuclei such as Pb, Sn, Ni, Ca, …
  hopefully in the future along isotopic chains

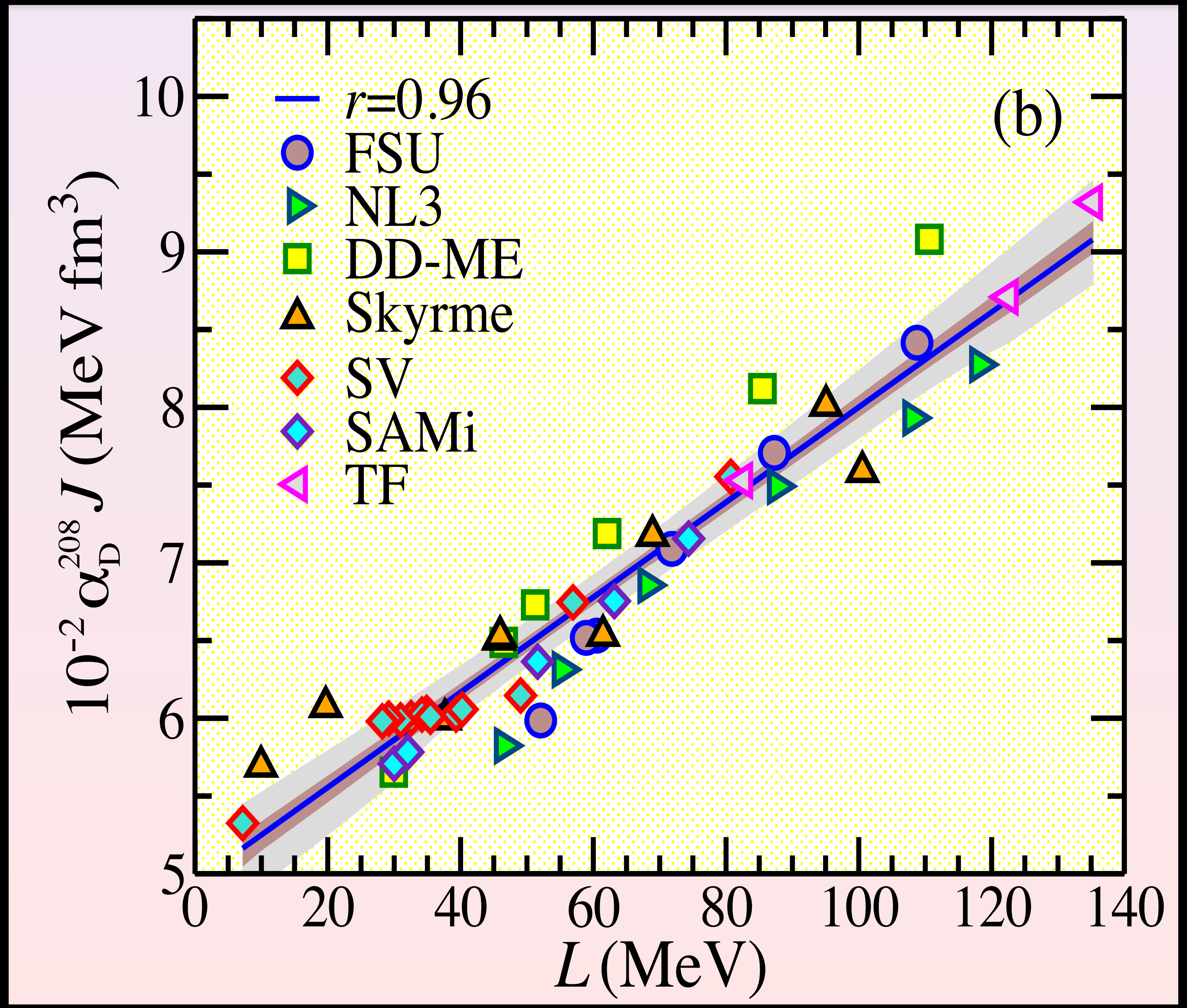
# Electric Dipole Polarizability $\alpha_D$

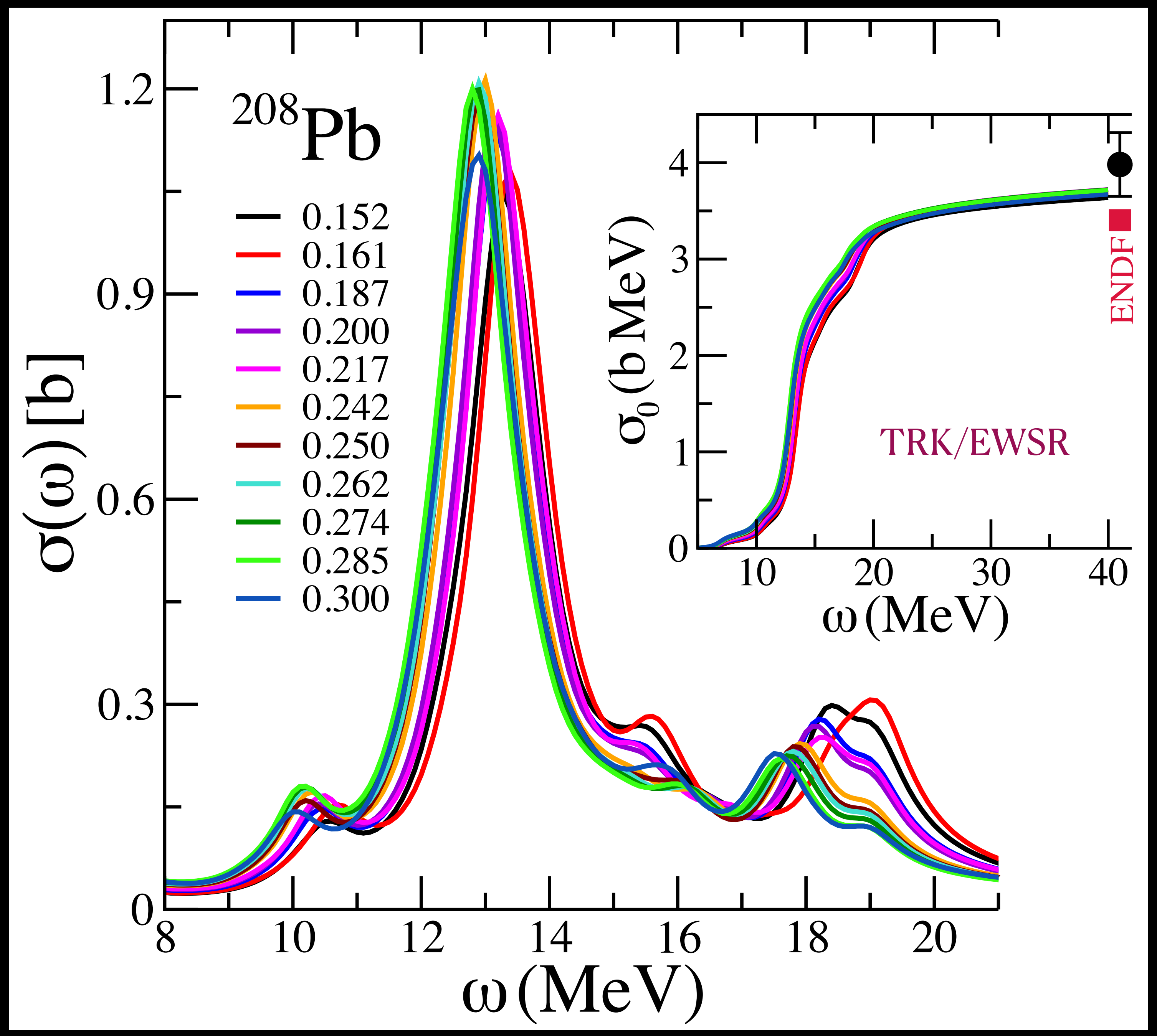
- A powerful electroweak complement to Rskin ($\gamma$-absorption experiments)
- Correlation to symmetry energy almost as strong as in the case of Rskin
- Energy weighted sum rule largely model independent
- Inverse energy weighted sum strongly correlated to L

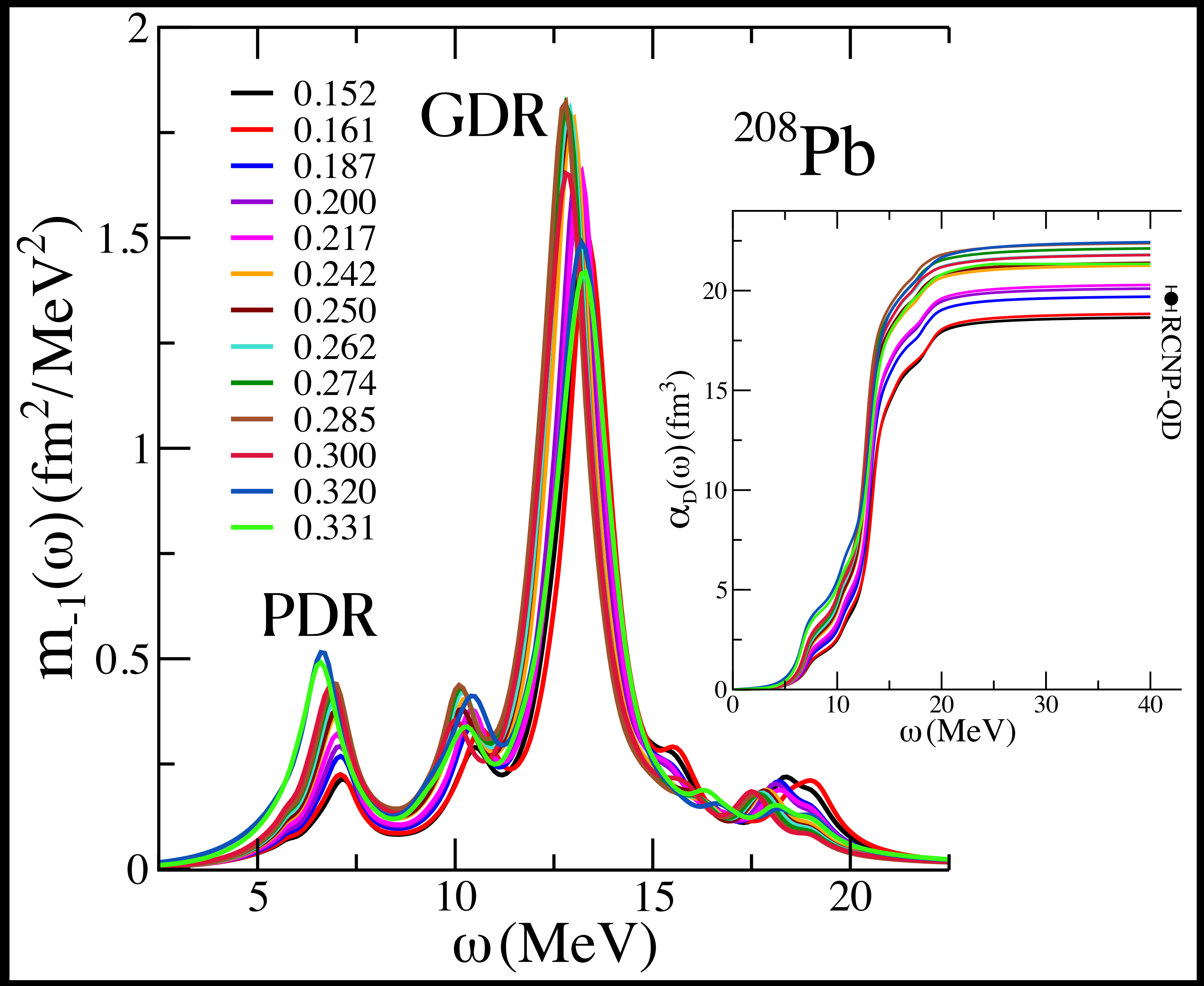
  Important contribution from PDR

$$\mathrm{EWSR} = \int_0^\infty \sigma(\omega)\,d\omega \approx 60\left(\frac{NZ}{A}\right)\ \mathrm{MeV\ mb}$$

$$\alpha_D = \left(\frac{\hbar c}{2\pi^2}\right)\int_0^\infty \frac{\sigma(\omega)}{\omega^2}\,d\omega = \left(\frac{8\pi e^2}{9}\right) m_{-1}$$

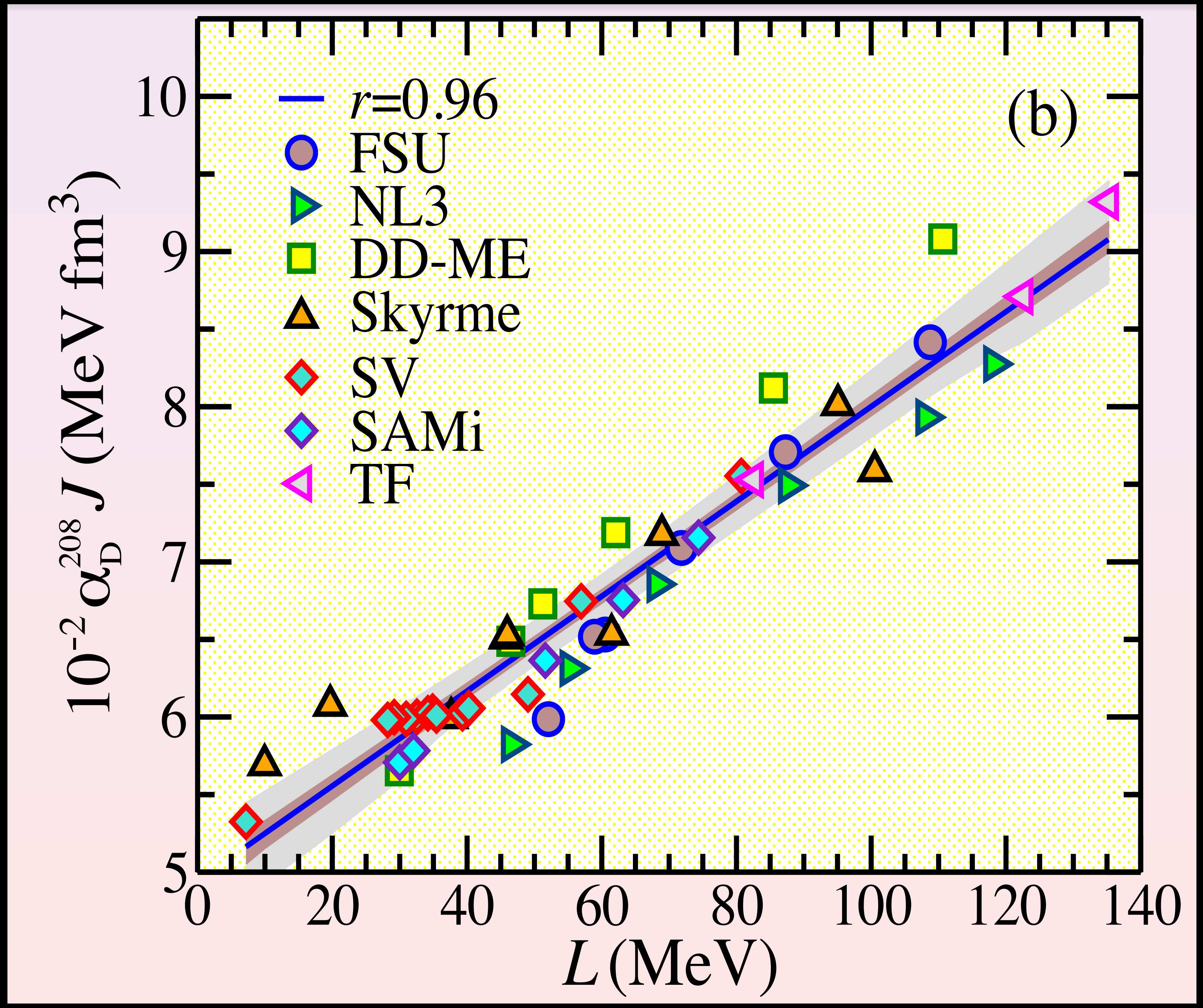


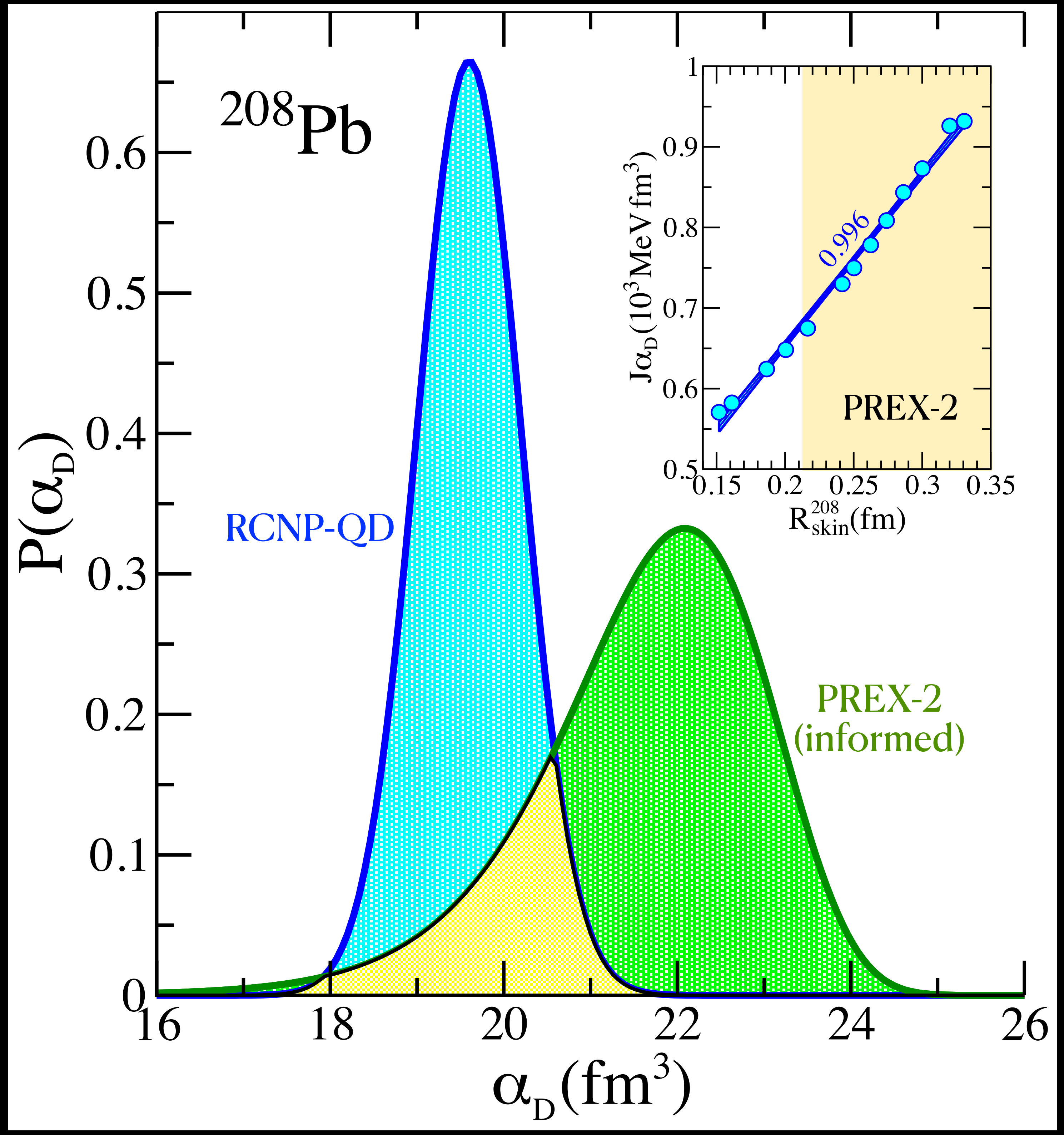


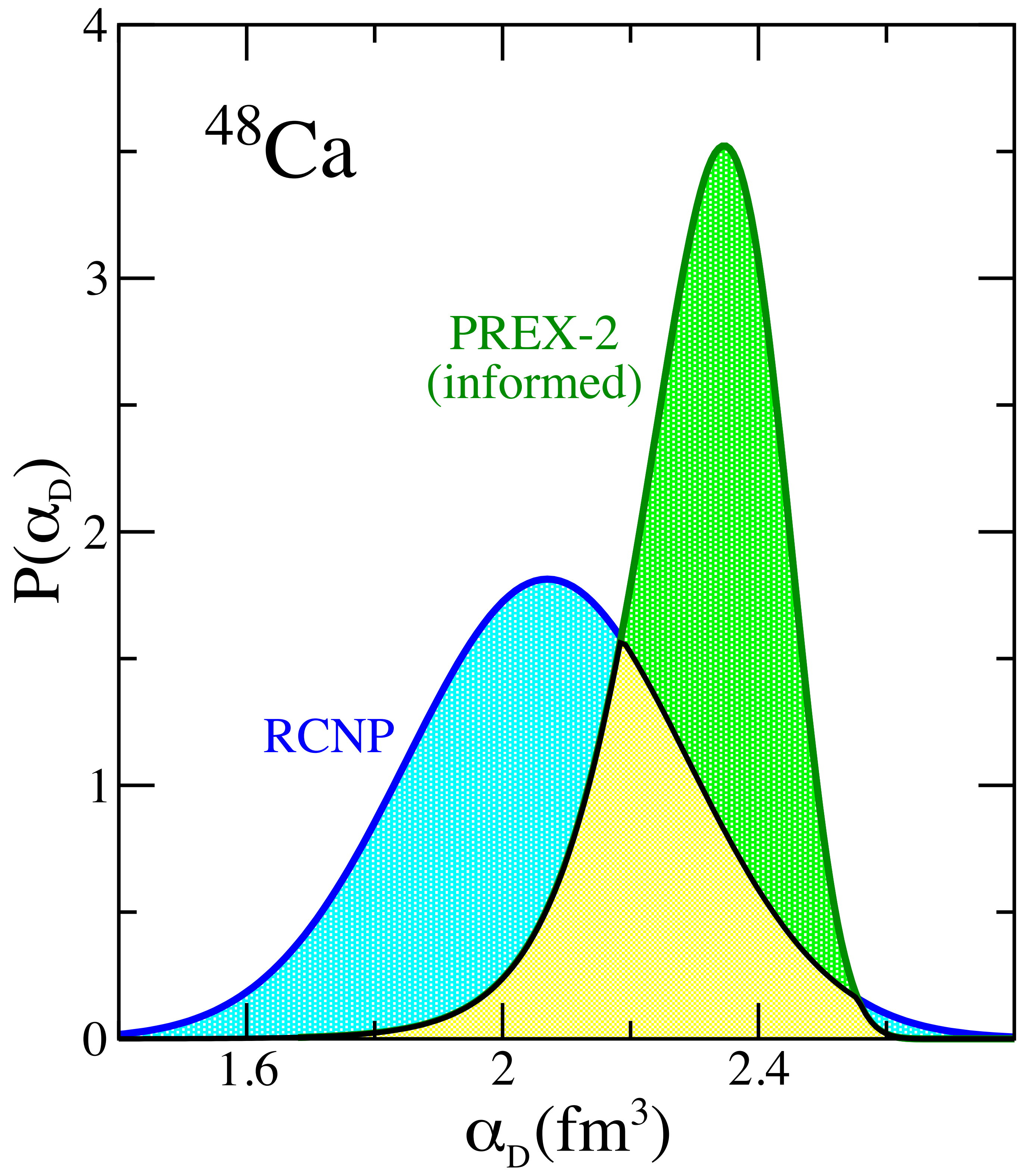


# Implication of PREX on $\alpha_D$

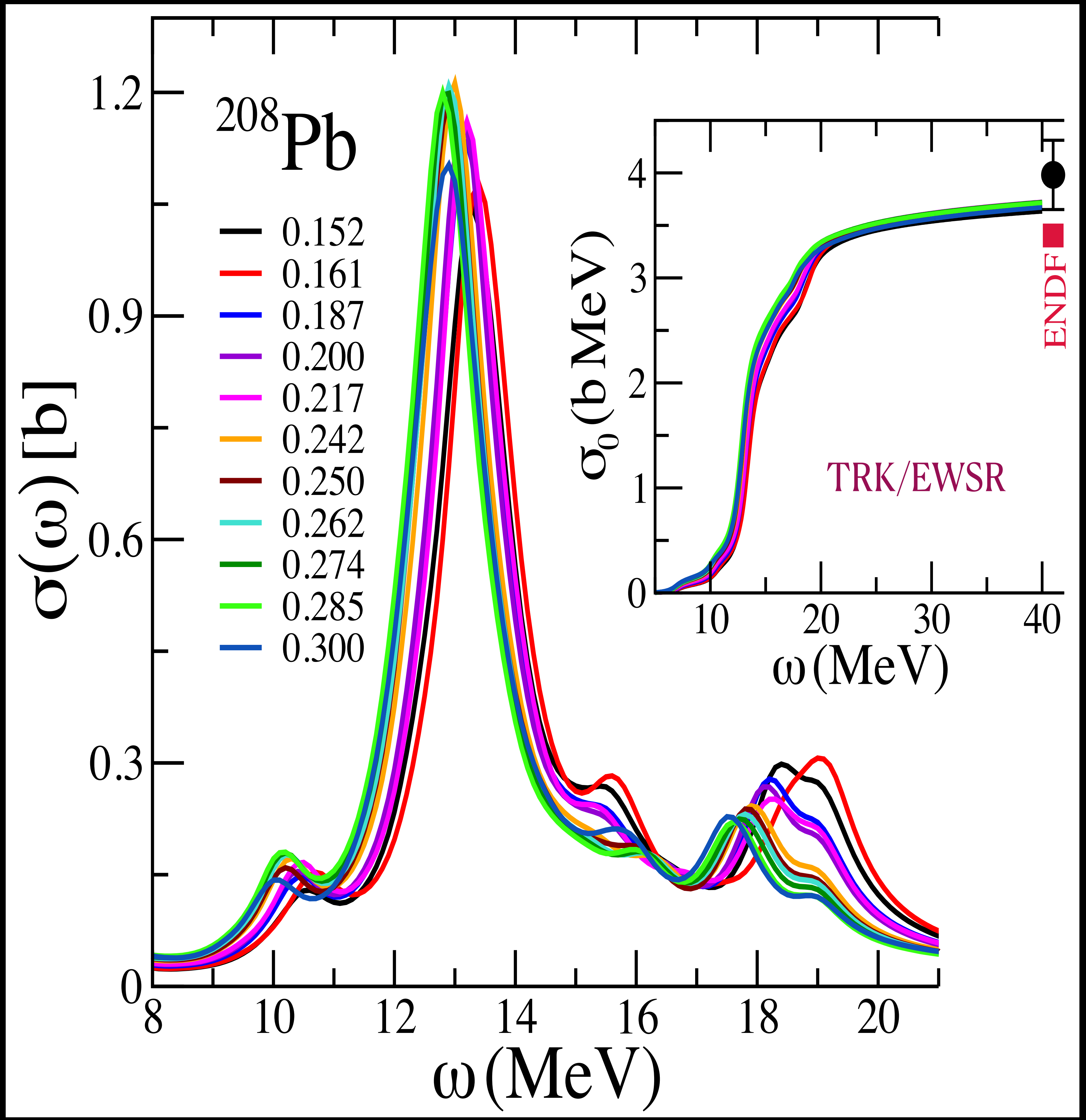
- A large and representative set of EDFs validate the strong correlation between $J\alpha_D$ and L
- For a representative set of covariant EDFs one determine the “PREX-informed” probability distribution of $\alpha_D$
- The PREX-informed probability distribution is in tension with the experimental determination from RCNP
- The PREX-informed extraction systematically overestimates the experimental results ($^{208}$Pb, $^{48}$Ca, $^{68}$Ni)

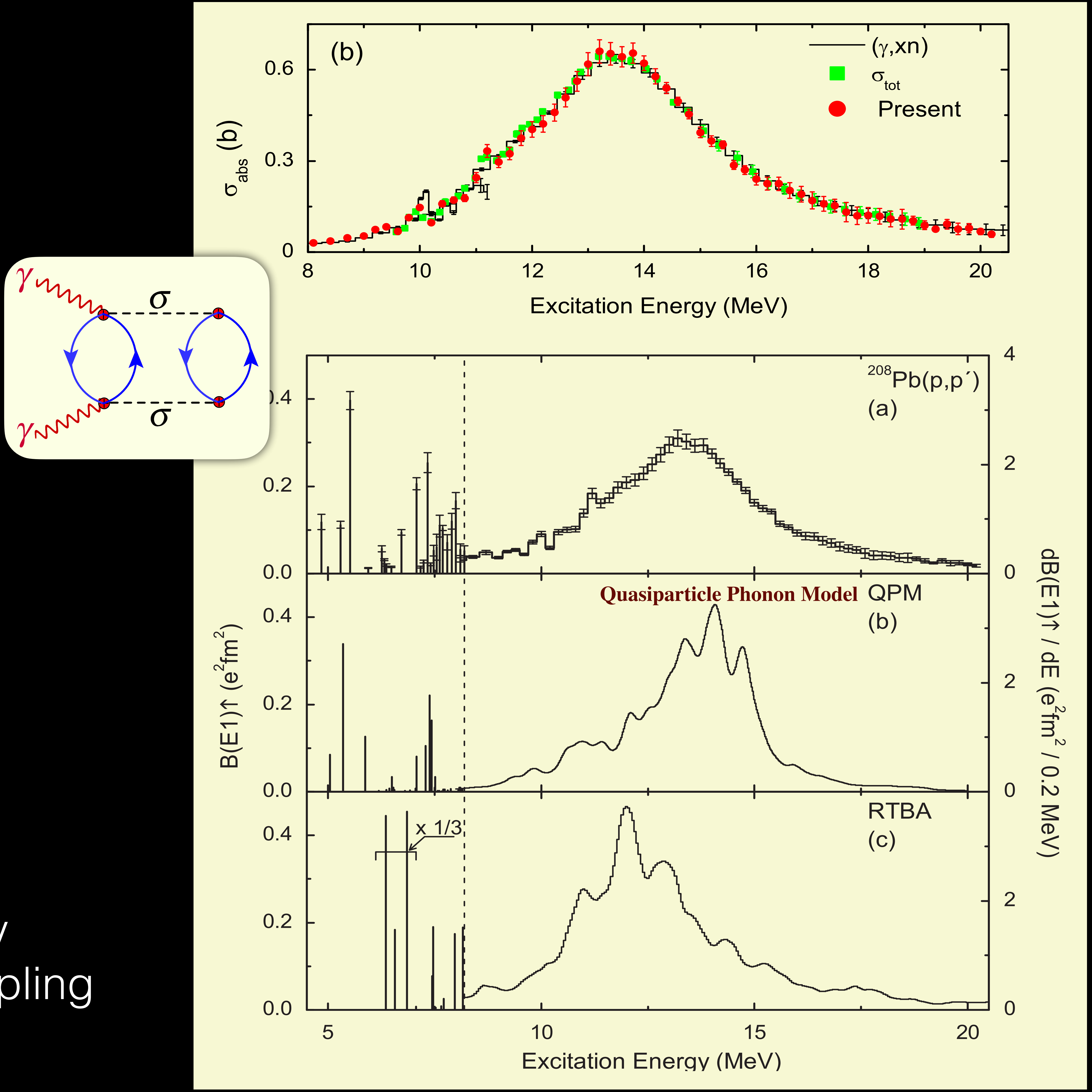






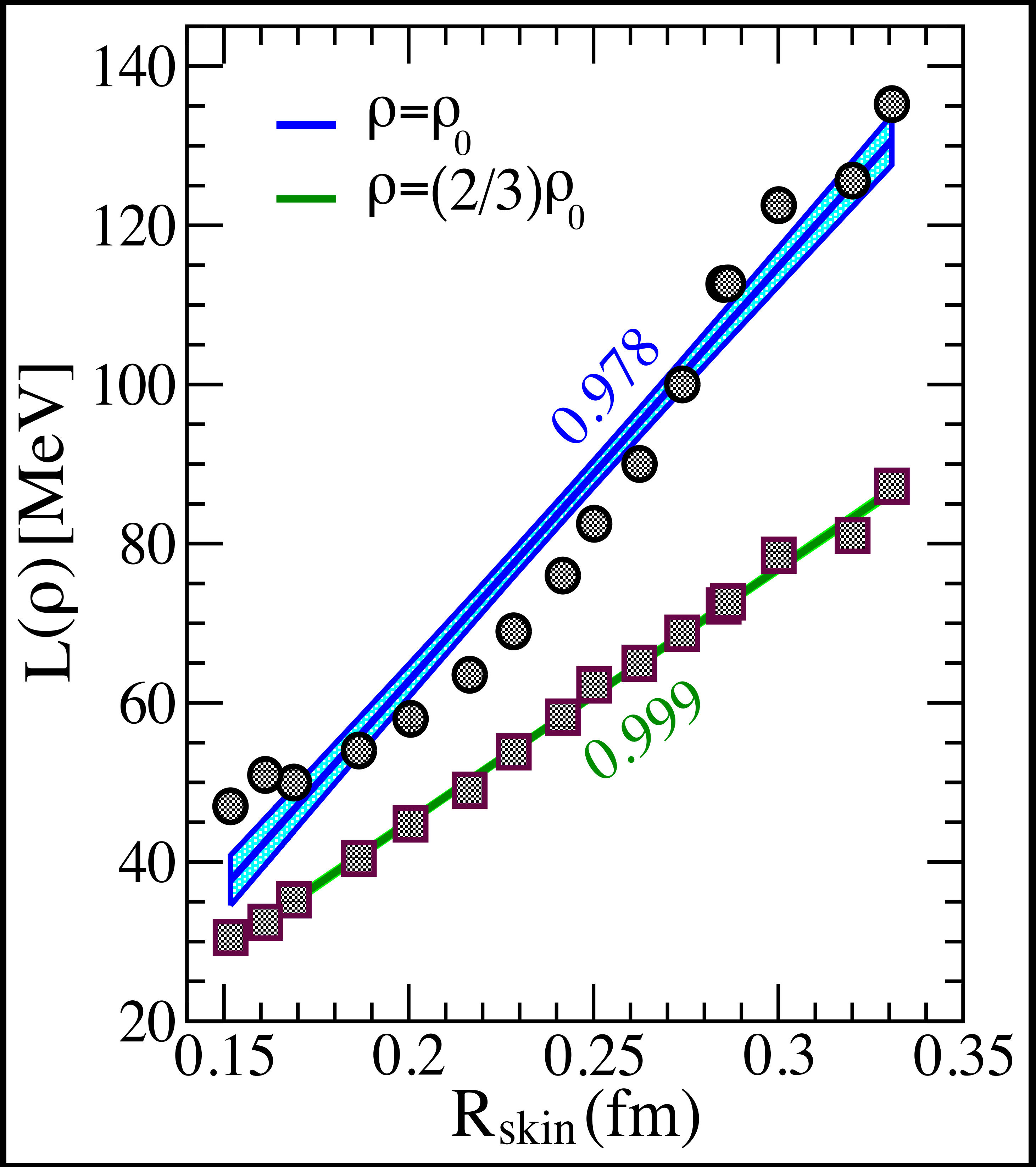
# Some Limitations of the DFT Approach



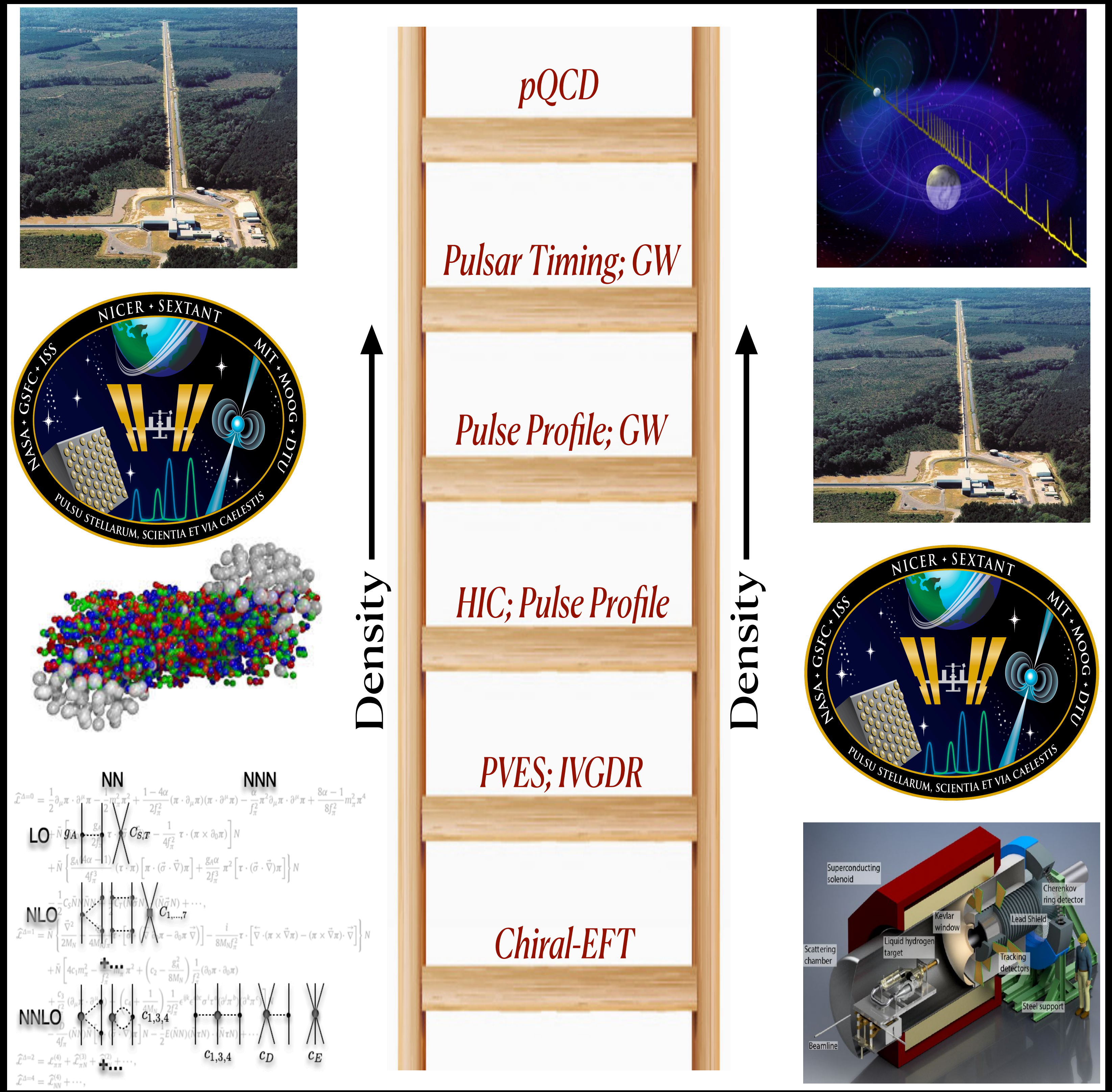


- RPA treats the continuum (escape) width correctly
- Not so the spreading width — emerging from coupling to more complicated (2p-2h, …) configurations!

# Building Bridges/Rungs: The Nuclear Equation of State Ladder

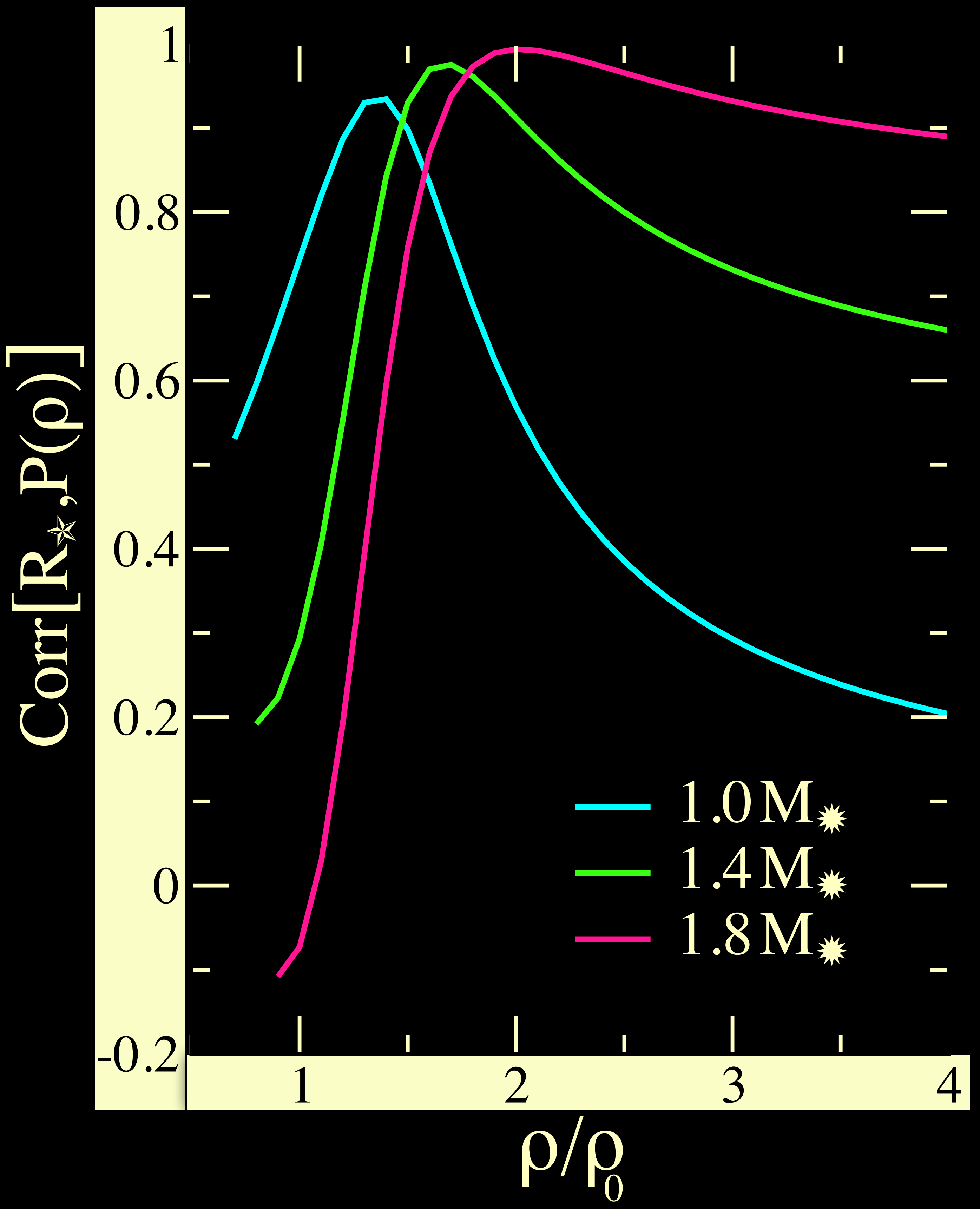


PVES/IVGDR informs the EOS of Neutron Rich Matter in the vicinity of $\rho_0$



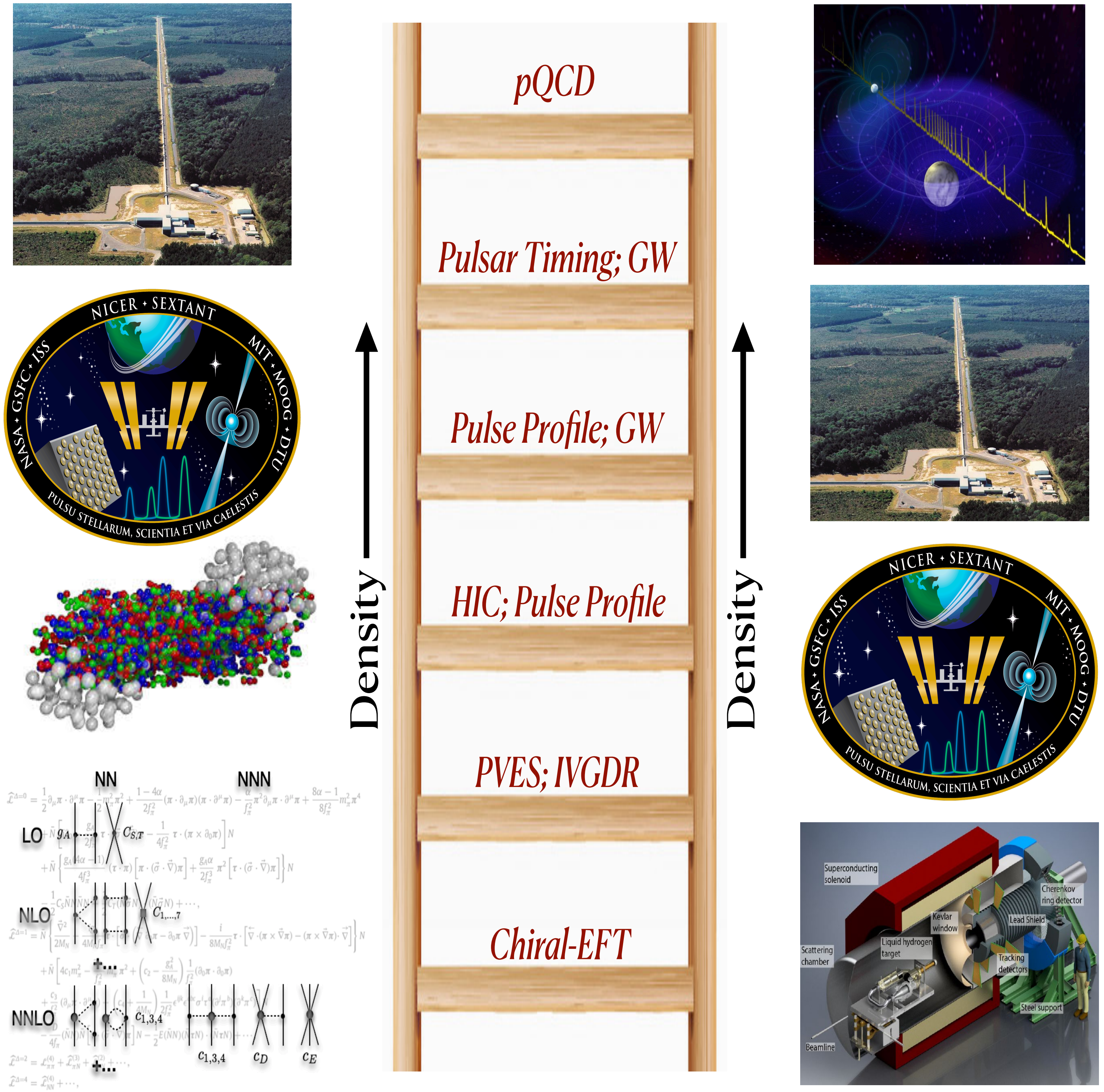
**Nuclear EOS Density Ladder**

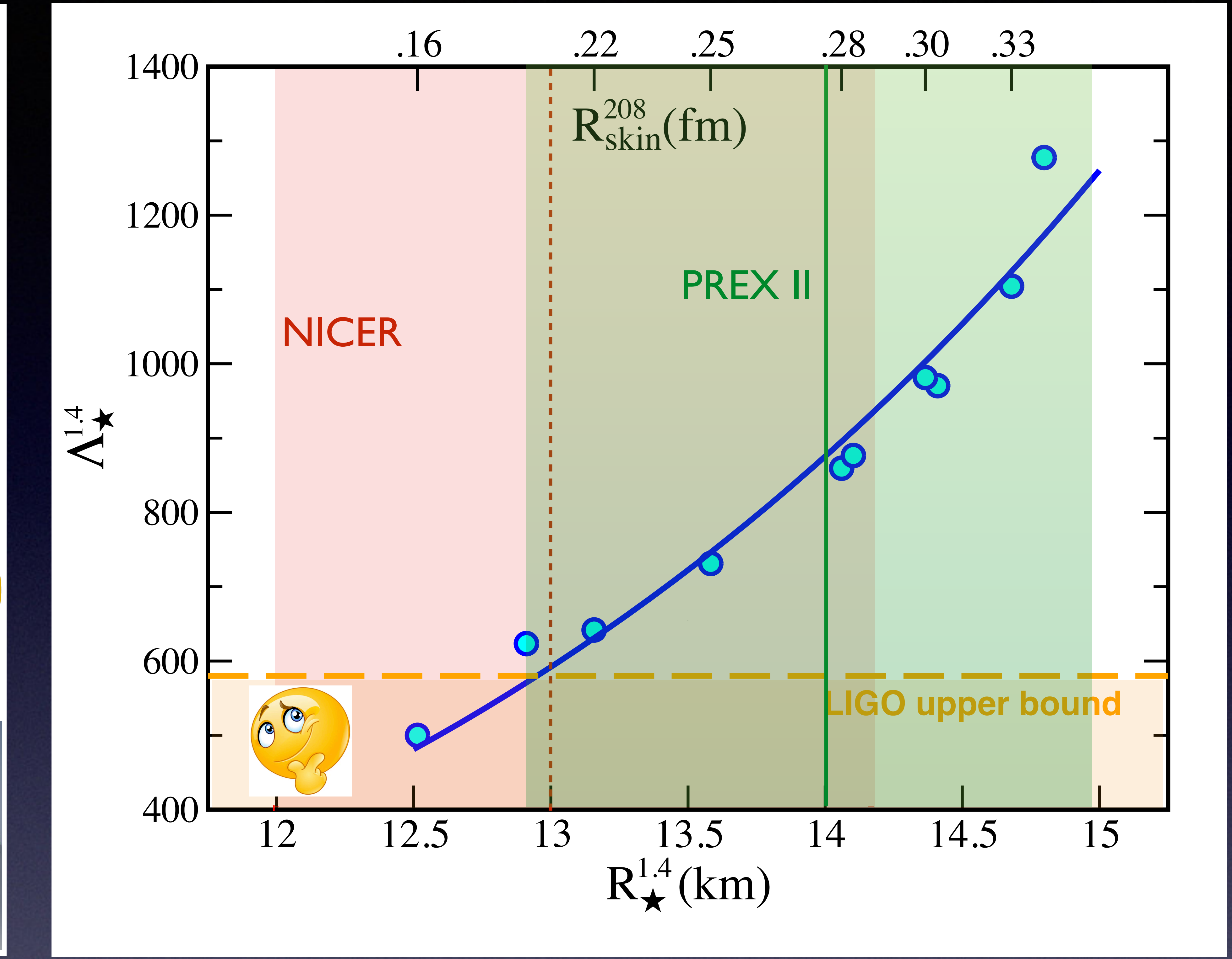
The **EOS** ladder has "rungs" of objects with certain properties that let scientists confidently measure the **EOS**. Jumping to each subsequent rung relies on methods for measuring objects that are ever **denser**, the next step often piggybacking on the previous one.

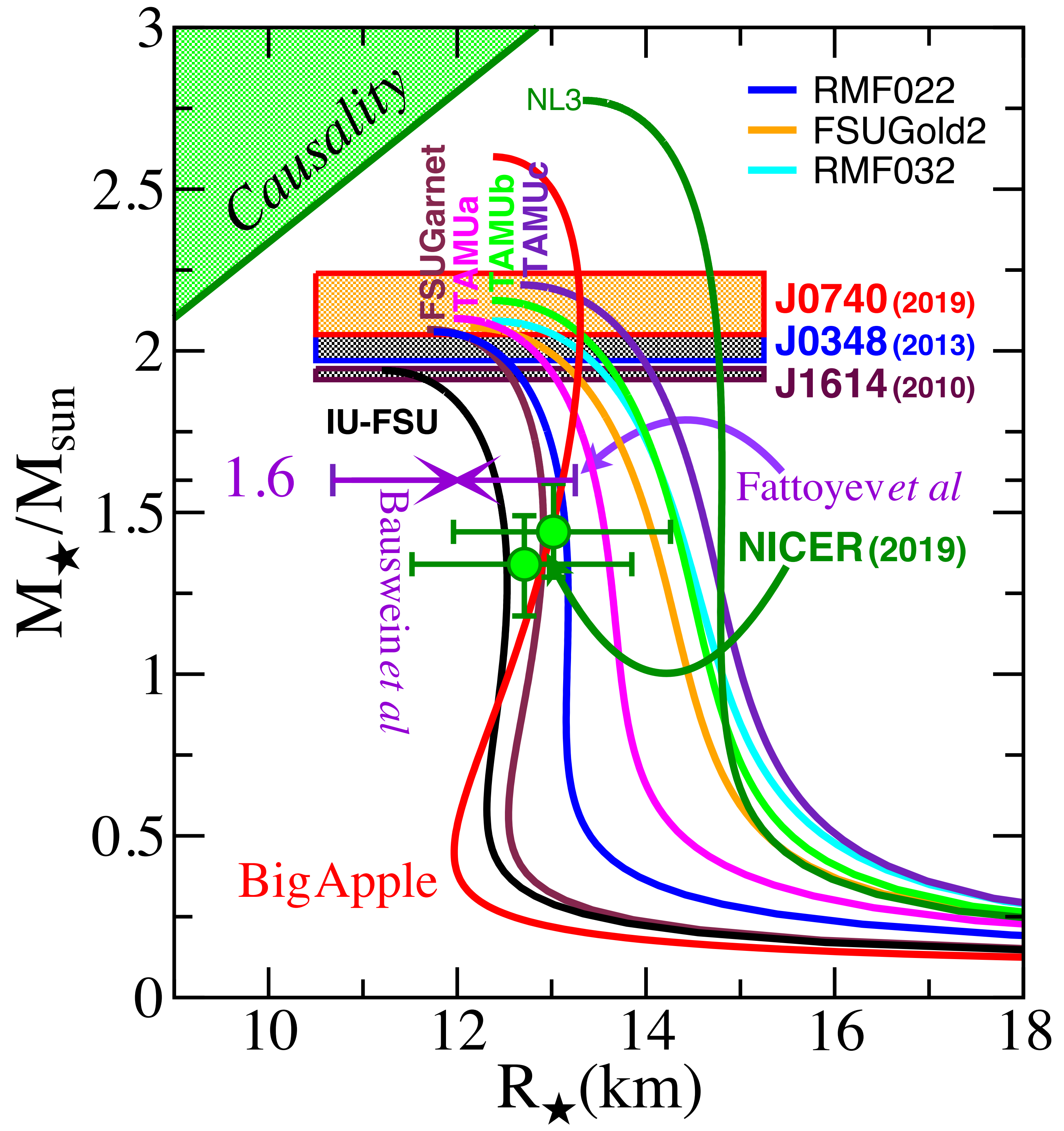


Pulse profile/GW informs the EOS of Neutron Rich Matter in the vicinity of 1.5-2 $\rho_0$

# The Golden Era of Neutron Star Physics







## Tantalizing Possibility

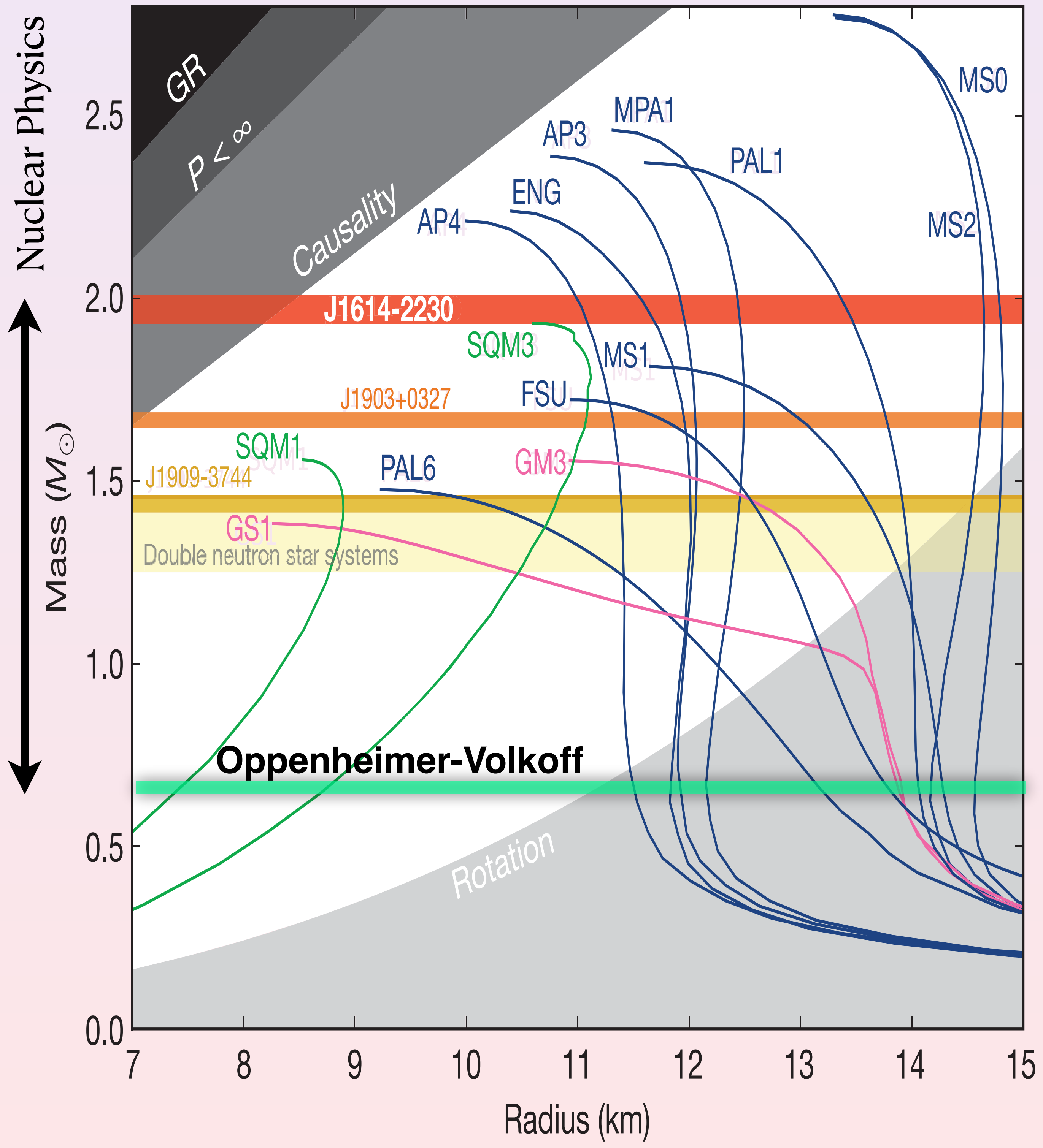
- *Laboratory Experiments suggest large neutron radii for Pb* $\lesssim 1\rho_0$
- *Gravitational Waves suggest small stellar radii* $\gtrsim 2\rho_0$
- *Electromagnetic Observations suggest large stellar masses* $\gtrsim 4\rho_0$

***Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?)***

# Backup Slides

# Neutron Stars: Unique Cosmic Laboratories

- Neutron stars are the remnants of massive stellar explosions (CCSN)
  Satisfy the TOV equations: Transition from Newtonian Gravity to Einstein Gravity
- Only Physics that the TOV equation is sensitive to: Equation of State
- Increase from 0.7 to 2 Msun transfers ownership to Nuclear Physics!



$$\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r)$$

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

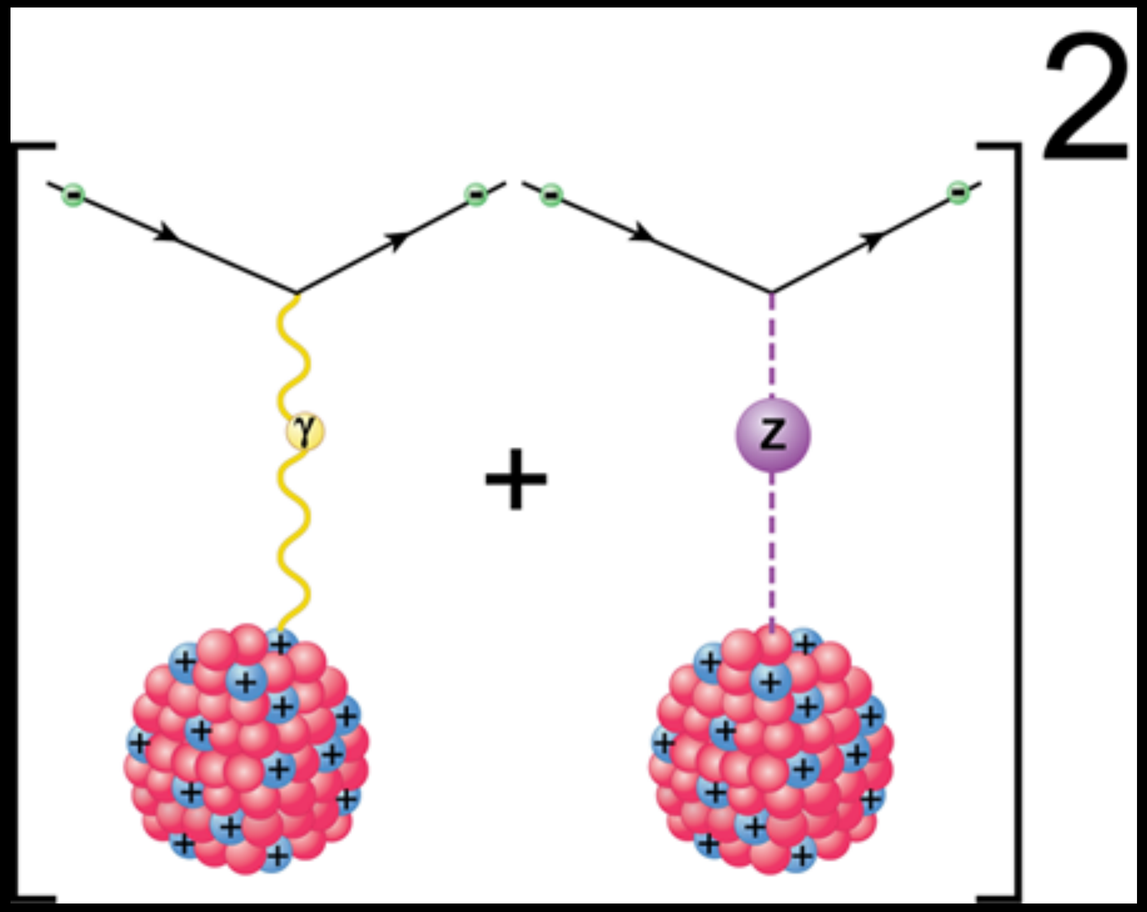
## Status before GW170817

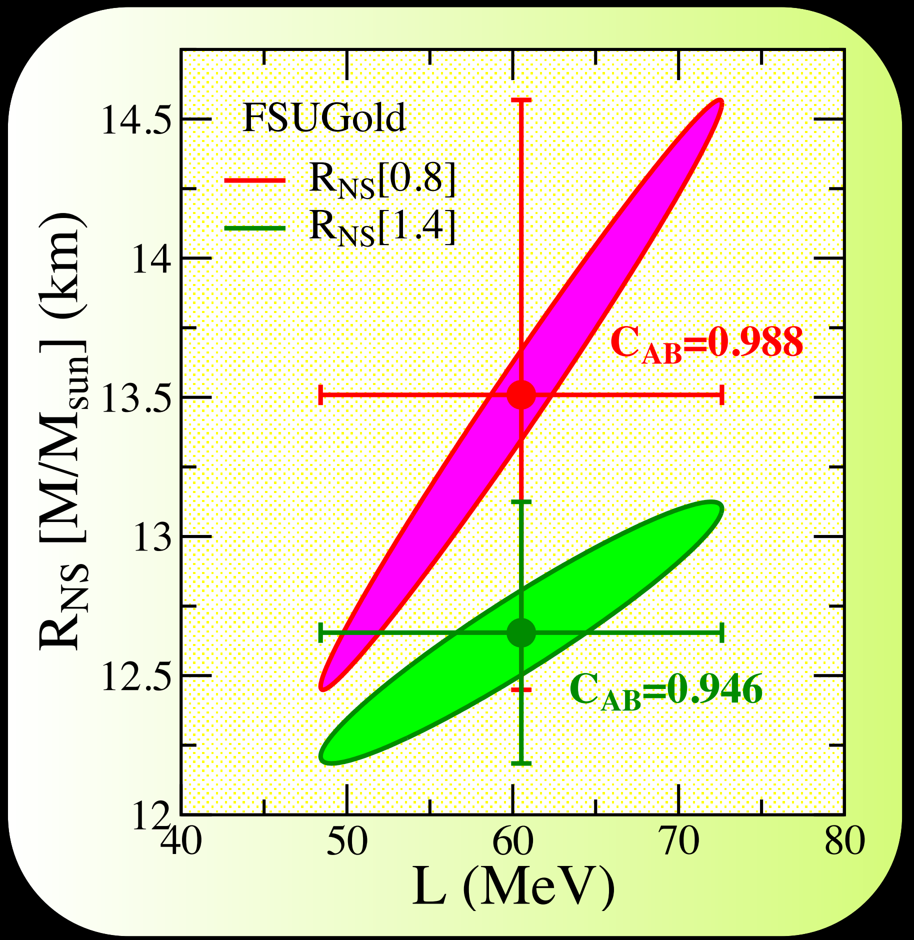
Many nuclear models that account for the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

Only observational constraint in the form of two neutron stars with a mass in the vicinity of $2M_{sun}$

# Heaven and Earth

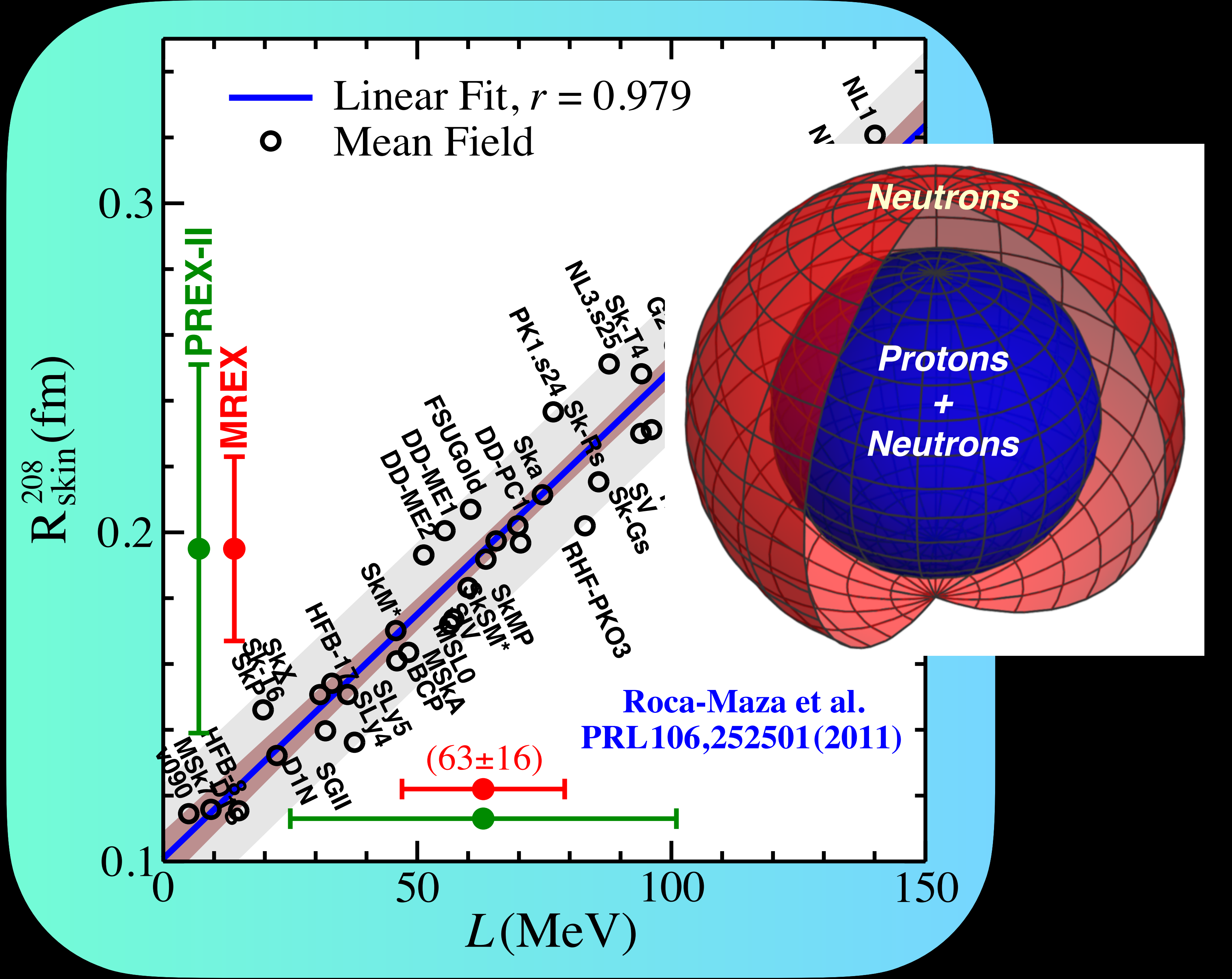
## Laboratory Constraints on the EOS

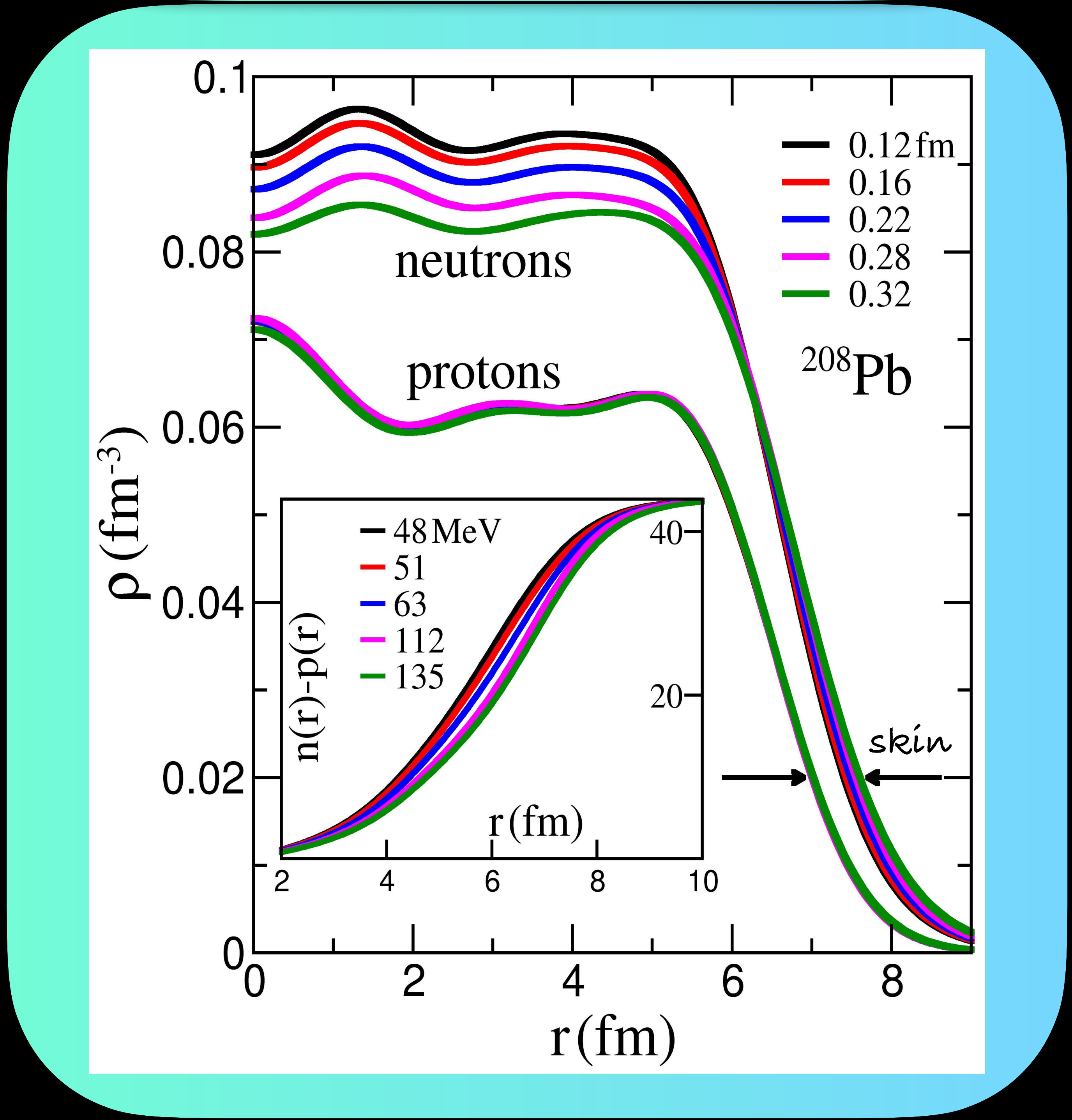




18 orders

magnitude

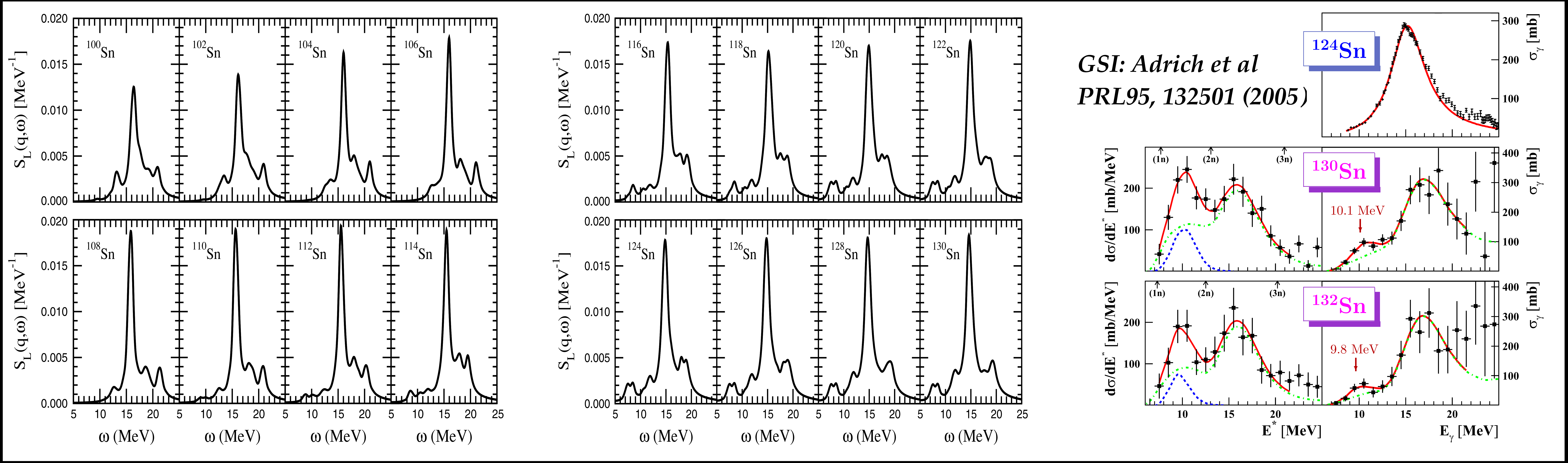




- Laboratory experiments constrain the EOS of pure neutron matter around saturation density: $P_{PNM}$=L
- Although a fundamental parameter of the EOS, L is not a physical observable — yet is strongly correlated to one: the neutron-rich skin of a heavy nucleus such as $^{208}$Pb
- Parity-violating elastic electron scattering is the cleanest experimental tool to measure the neutron radius of lead

# Electric Dipole Polarizability of Unstable Neutron-Rich Nuclei

Most stringent constraint on EOS of neutron-rich matter from nuclei with huge skins — preferably along long isotopic chains (e.g., tin)

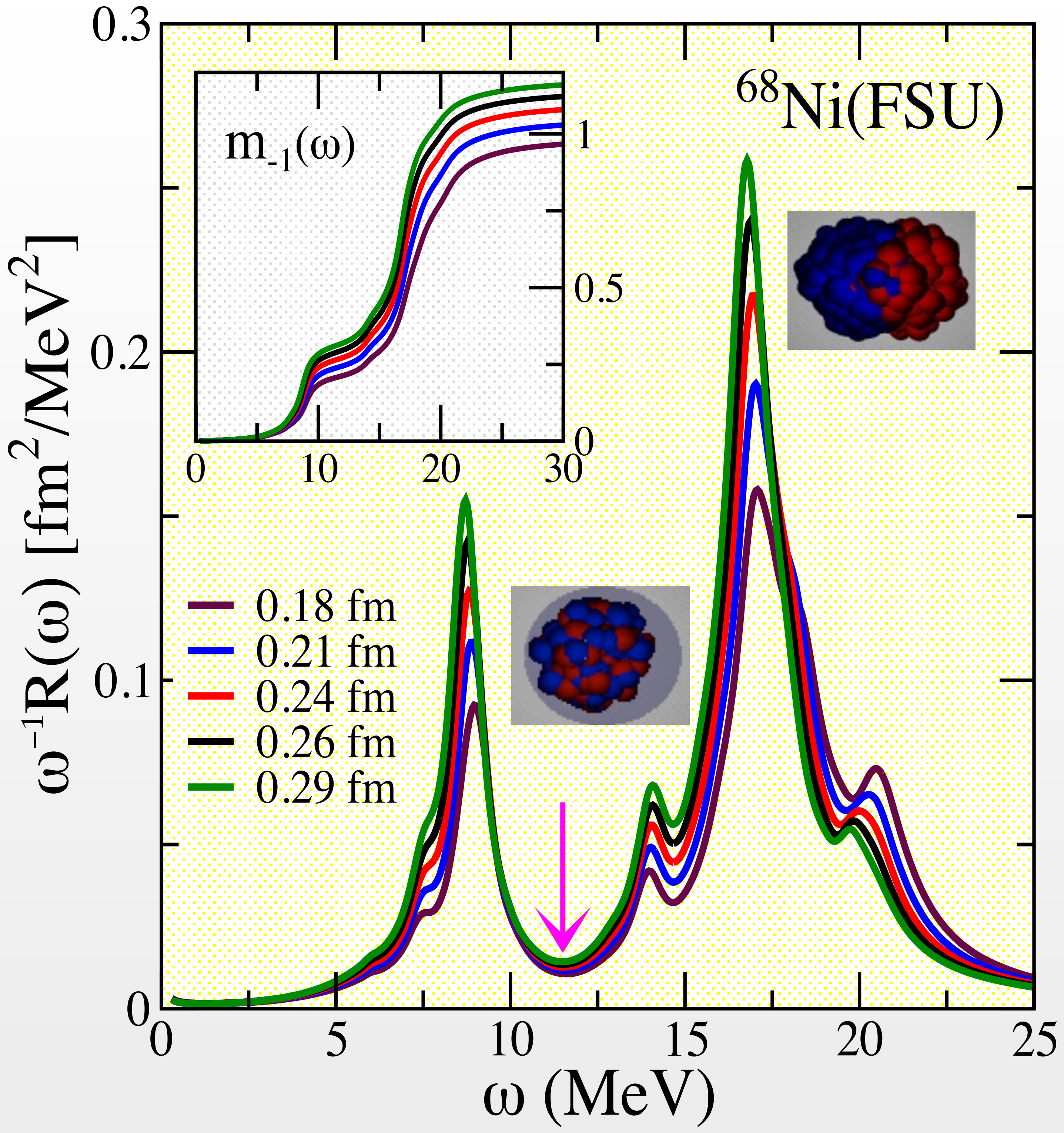


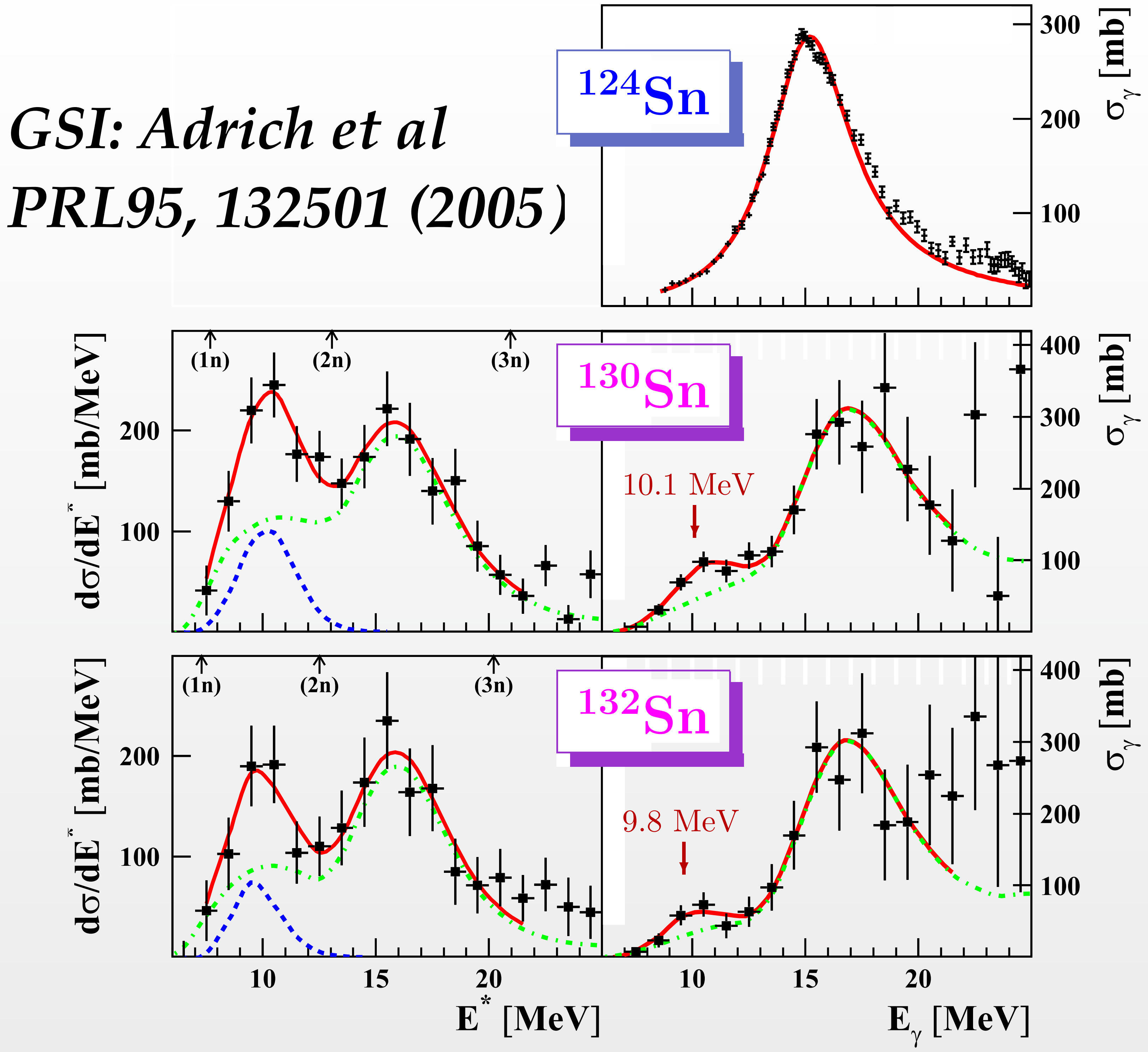
*GSI: Adrich et al*
*PRL95, 132501 (2005)*

# Electric Dipole Polarizability of Unstable Neutron-Rich Nuclei

Most stringent constraint on EOS of neutron-rich matter from nuclei with huge skins — preferably along long isotopic chains (e.g., tin)

Giant (Hercules) Awakes and Drives off the Pygmies by Lucas Cranach The Younger (1551)





*GSI: Adrich et al PRL95, 132501 (2005)*

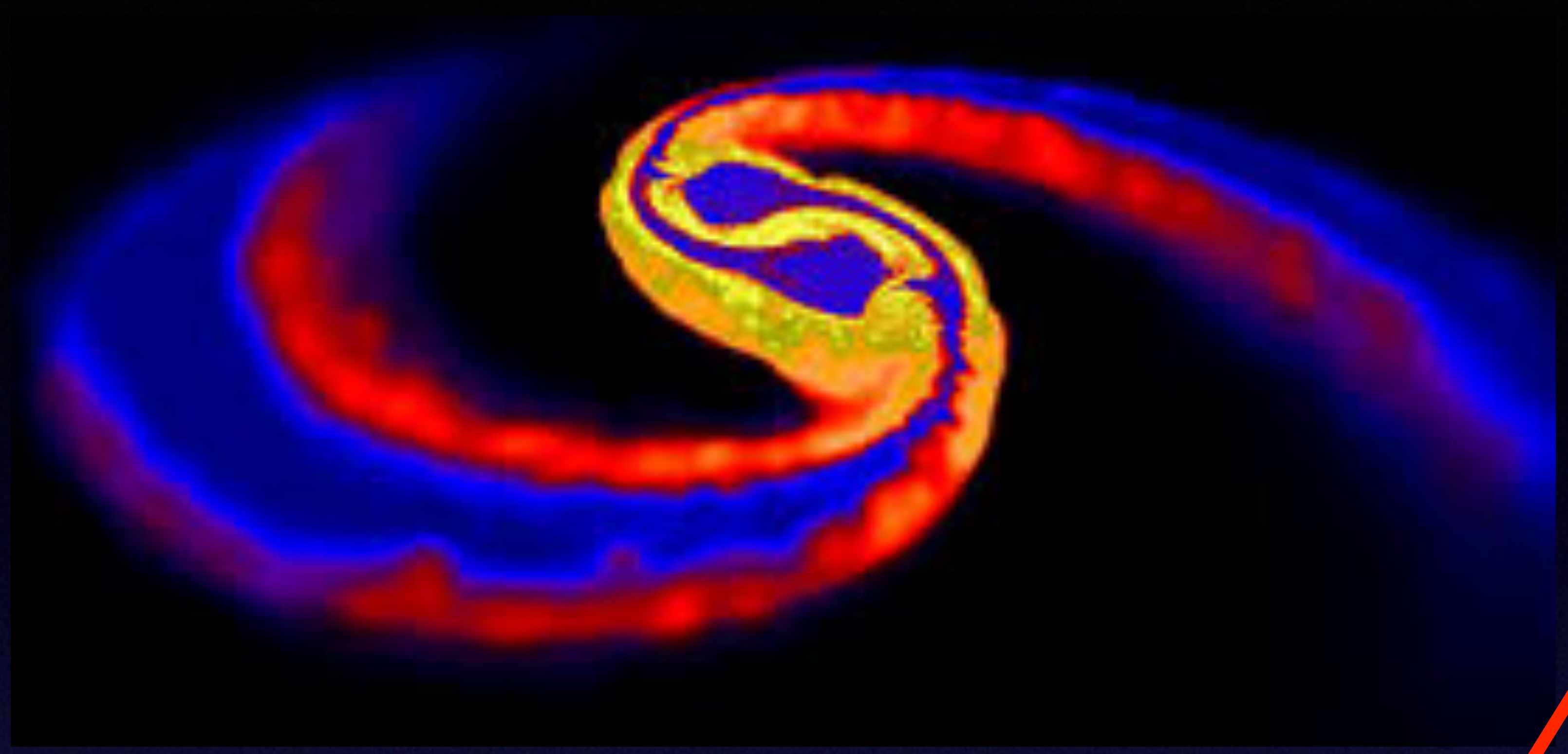
# Tidal Polarizability and Neutron-Star Radii (2017)

## Electric Polarizability:

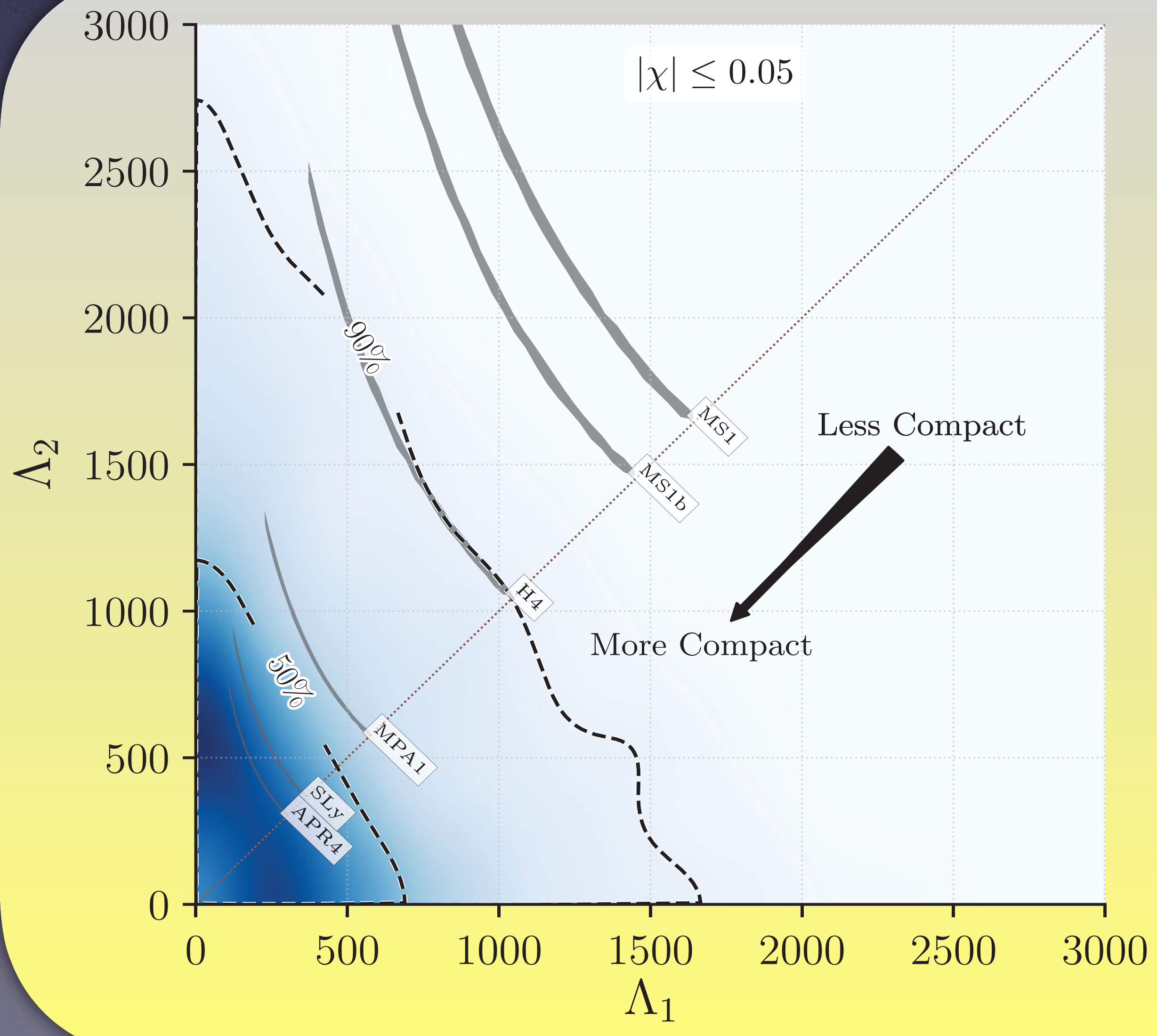
- Electric field induced a polarization of charge
- A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$

## Tidal Polarizability (Deformability):

- Tidal field induces a polarization of mass
- A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$



$$\Lambda = k_2 \left( \frac{c^2 R}{2GM} \right)^5 = k_2 \left( \frac{R}{R_s} \right)^5$$



GW170817
rules out very large
neutron star radii!

Neutron Stars
must be compact

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation. Very sensitive to stellar radius!